A Closer Look at Energy Performance of Buildings: Simulated vs. Measured

Tianzhen Hong, PhD, PE
March 3, 2011
Simulation Research Group
Lawrence Berkeley National Laboratory

Acknowledgement

My research and this presentation benefited from projects I worked with other groups:

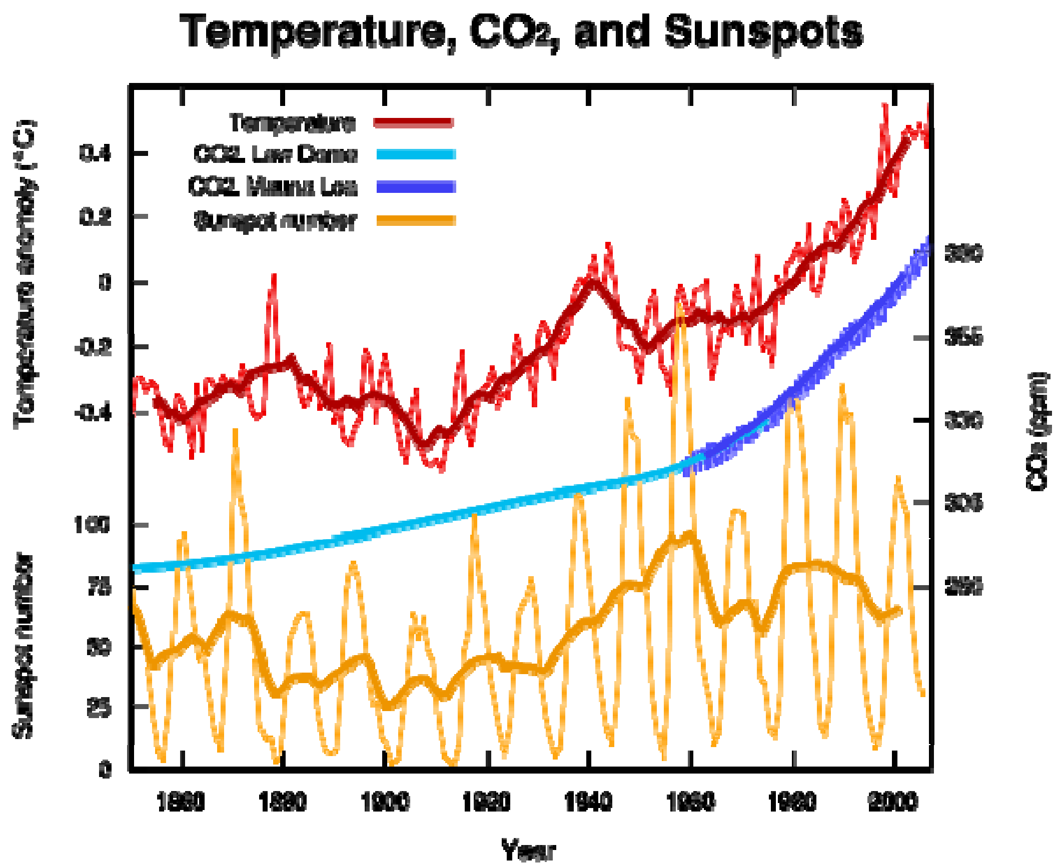
- Windows and Daylighting Group
- China Energy Group
- Lighting Systems Group
- Applications Team
- Commercial Building Ventilation and Indoor Environmental Quality Group
- Commercial Buildings Group

Outline

- The Big Picture
- Energy Performance of Buildings
  – Measured and Simulated
- Discrepancies between Simulated and Measured Energy Performance
- Two Case Studies
  – Space Cooling Energy Use of Data Centers
  – Space Heating Energy Use of Office Buildings
- Better Simulation

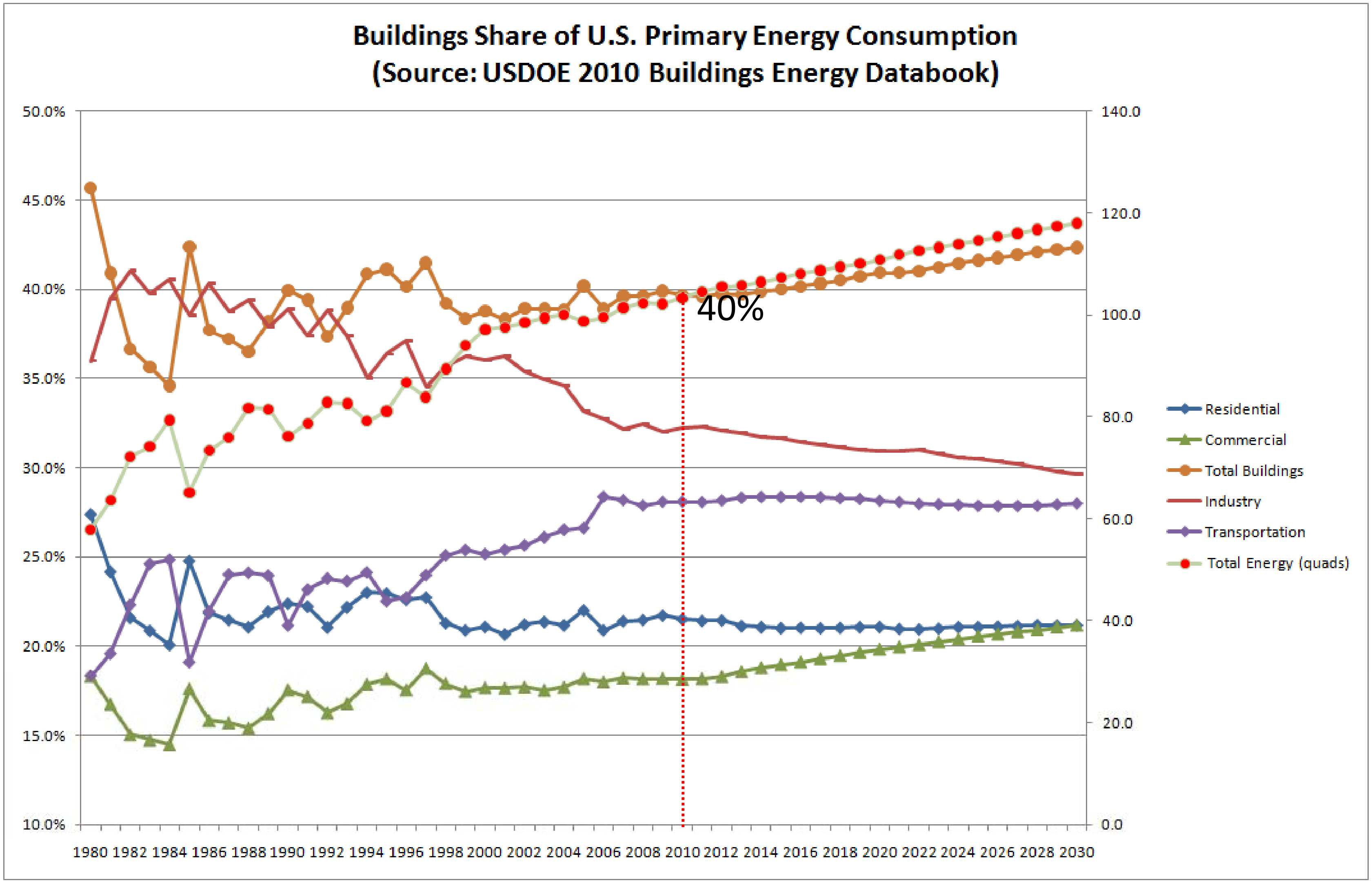
Global Climate Change

Source: WWF

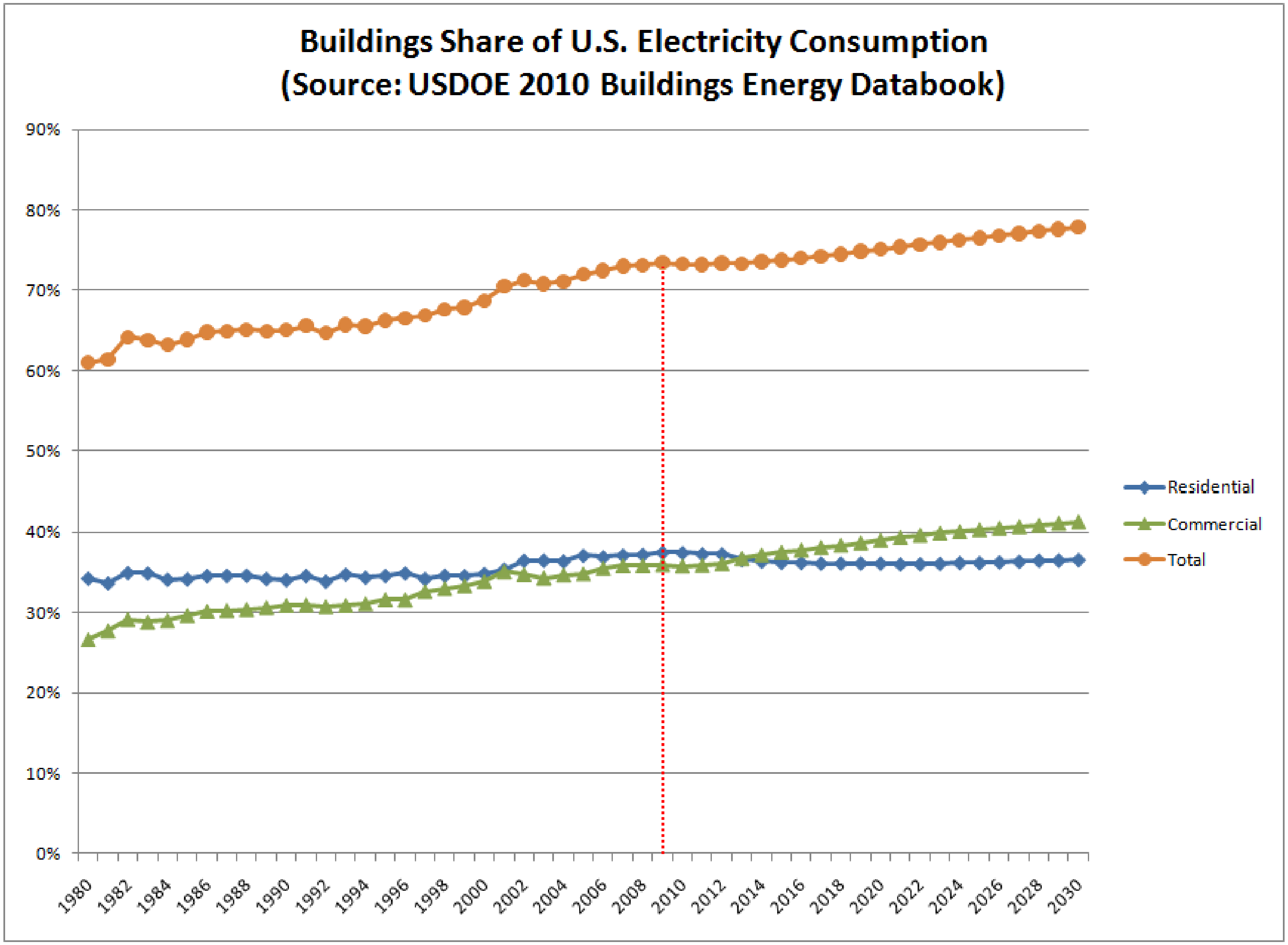


Source: Solar Center, Stanford

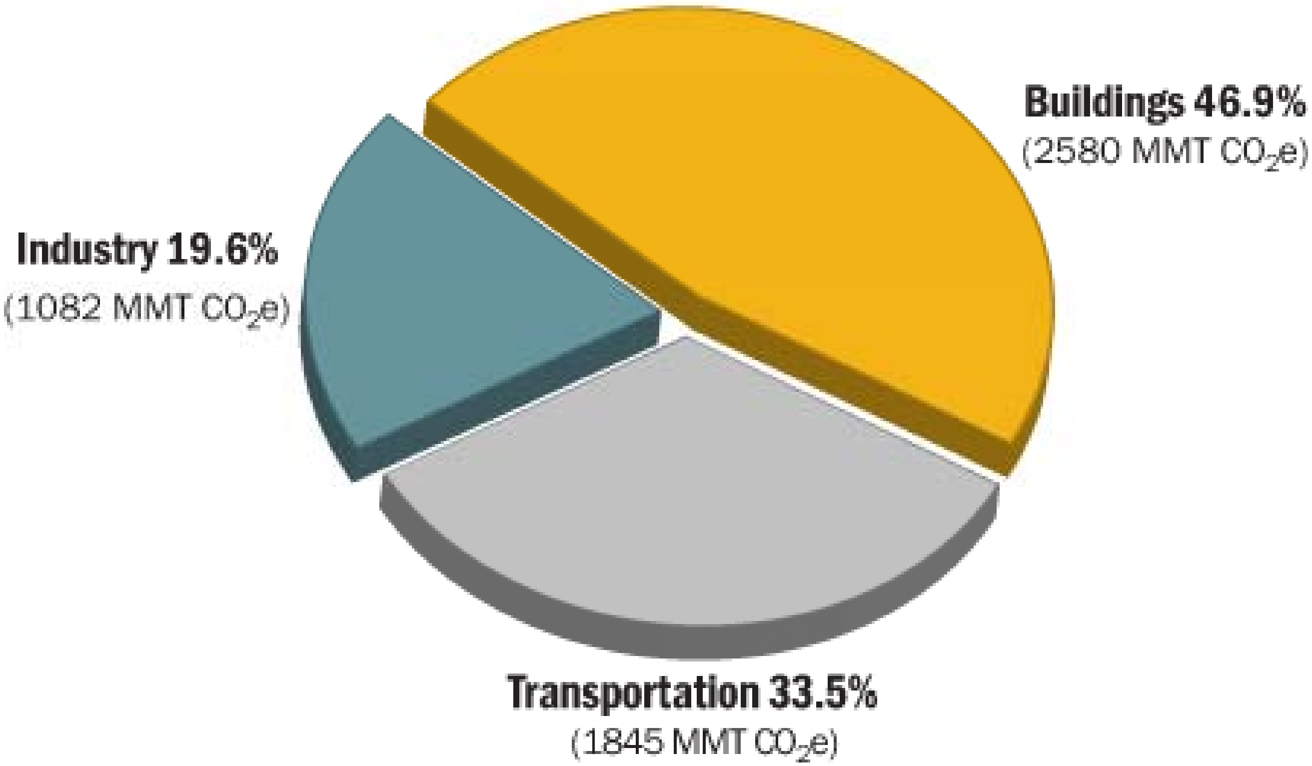
U.S. Primary Energy Consumption



U.S. Buildings Electricity Consumption



U.S. CO_2 Emissions



U.S. CO_2 Emissions by Sector

Data Source: U.S. Energy Information Administration (2009).

Energy Efficiency is a National Priority

"Each and every one of us can start thinking about how can we save energy in our homes, in our buildings."

President Barack Obama
Feb 10, 2009

On February 3, 2011, President Obama announced the **Better Buildings Initiative** - to improve the energy efficiency of existing commercial buildings by 20% by 2020

Energy Performance of Buildings

Why some buildings consumed so much more energy than others with similar functions?

How feasible is it to reach the NZEB goal?

Back to Basics - understanding energy use of buildings is the most important step towards energy savings:

- Where energy is used?
- How much energy is used?
- When energy is used?
- How energy is used?
- Who and why uses the most amount of energy?
- To identify waste, deficiency, and savings opportunities!

Energy Performance of Buildings

Two methods to obtain energy use of buildings:

- Measurement
  - Beyond monthly utility bills
  - Real data, ‘trust without questions’
  - Can be time-consuming and costly for detailed measurement
- Simulation
  - Provide very detailed results – end uses, monthly, sub-hourly, systems/components/zones levels
  - ‘Quick’ and cost-effective
  - Questionable results
- Both methods are needed!

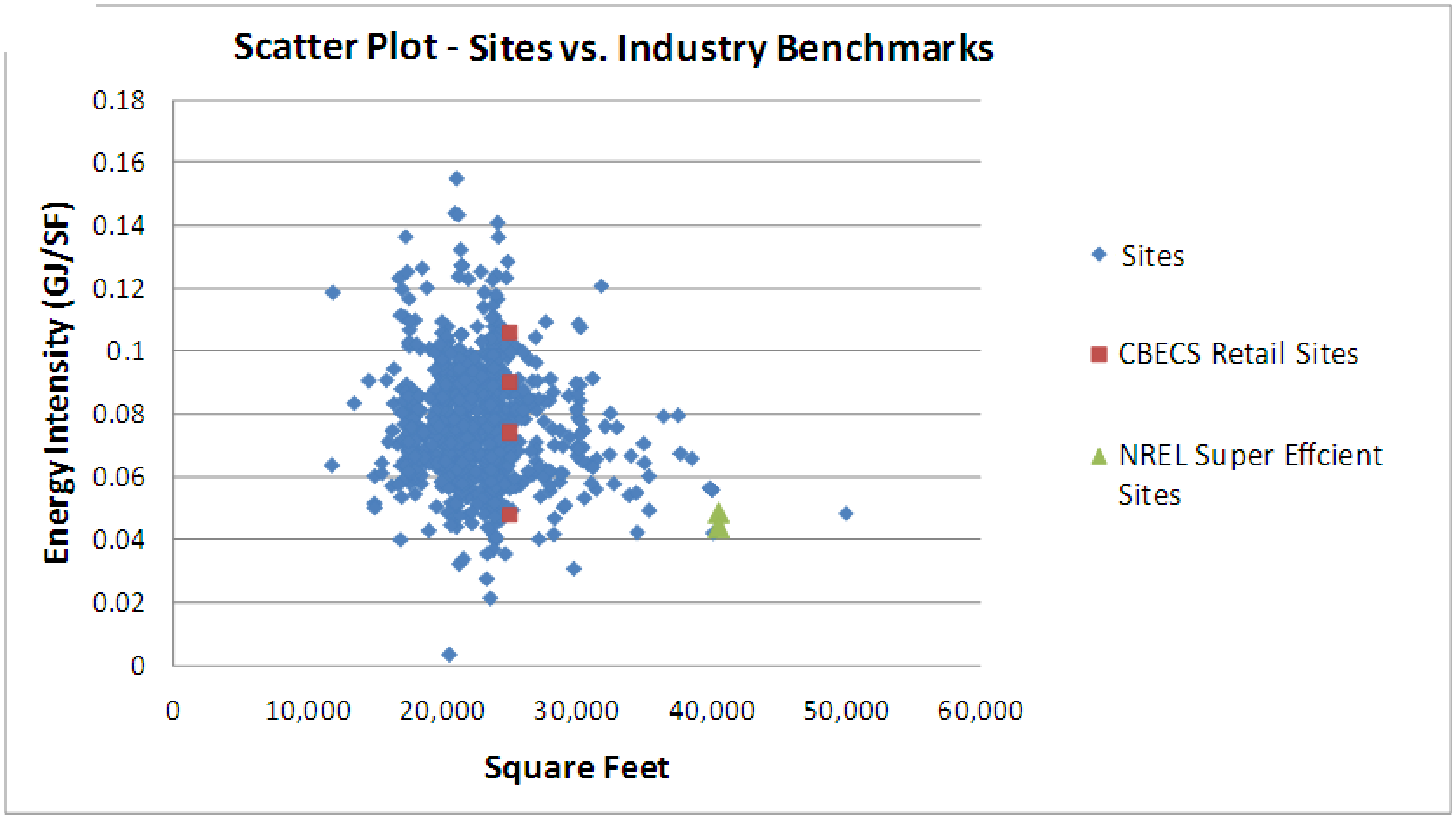
Why Need Measurement?

- Real data help understand energy performance of buildings
- Verify energy and demand savings from retrofit and commissioning
- Obtain operational rating, e.g. ASHRAE bEQ
- Obtain LEED certificate for existing buildings
- *Sometimes, to help verify or calibrate simulation models*
- Other reasons…

Why Need Simulation?

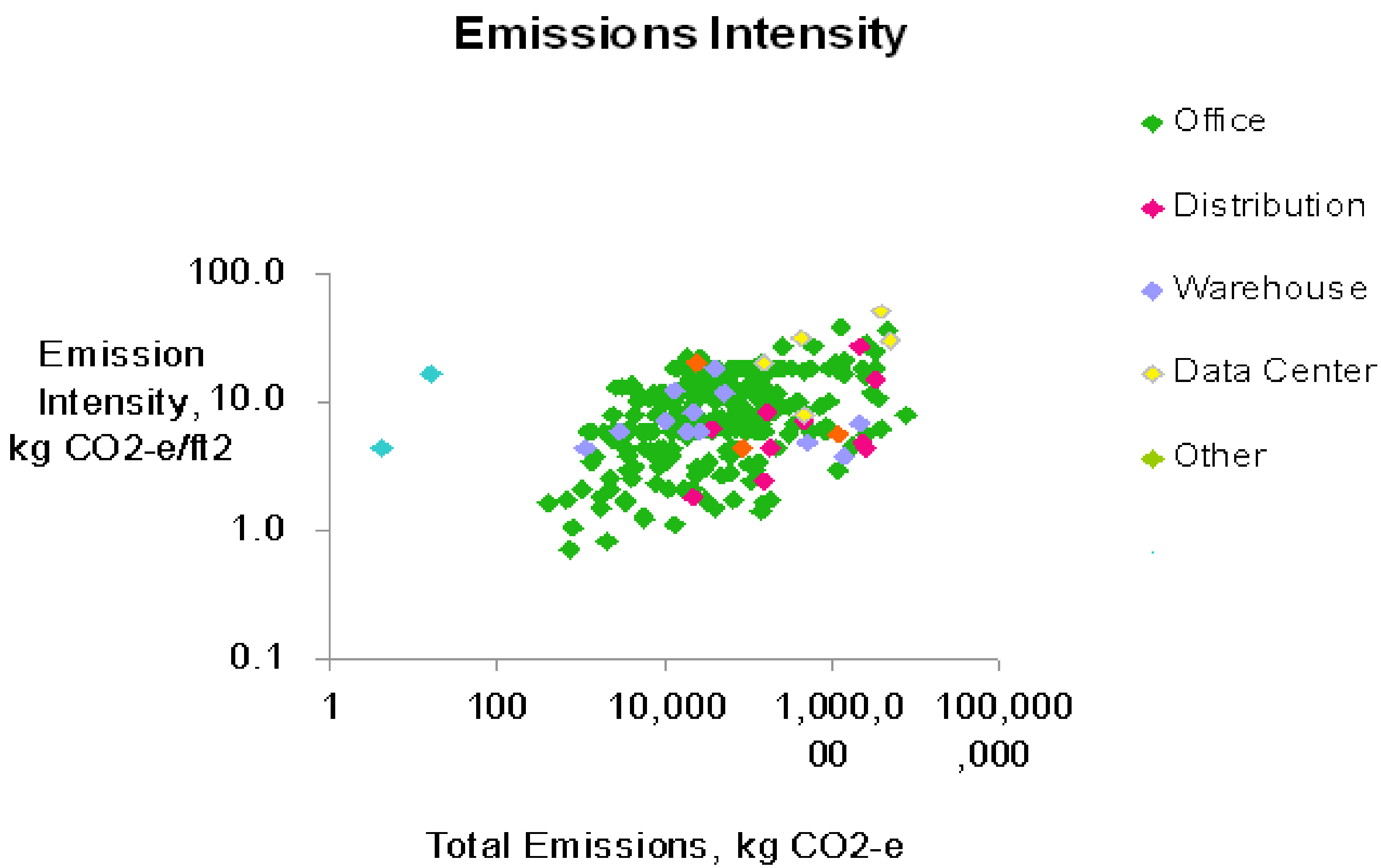
- Evaluate design alternatives to help make better decisions for new buildings
  - Unconventional, innovative low energy designs that cannot rely on rules-of-thumb or previous design experience
- Demonstrate code compliance using the performance path when prescriptive path is not allowed, e.g. WWR >40% in ASHRAE 90.1-2010
- Building energy benchmarking, rating, labeling
  - LEED certification, ASHRAE Building EQ
  - Incentive programs: SBD, EPAct §179D Federal Tax Credit
- Identify and evaluate retrofit measures for existing buildings
- Used in the development of building energy code and standards
- **Sometimes** to predict actual energy use of buildings

Measured Energy Performance (1)



Profile of Measured Energy Use of Big-Box Retails in US and Canada
Source: ICF International

Measured Energy Performance (2)



Source: ICF International

Measured Energy Performance (3)

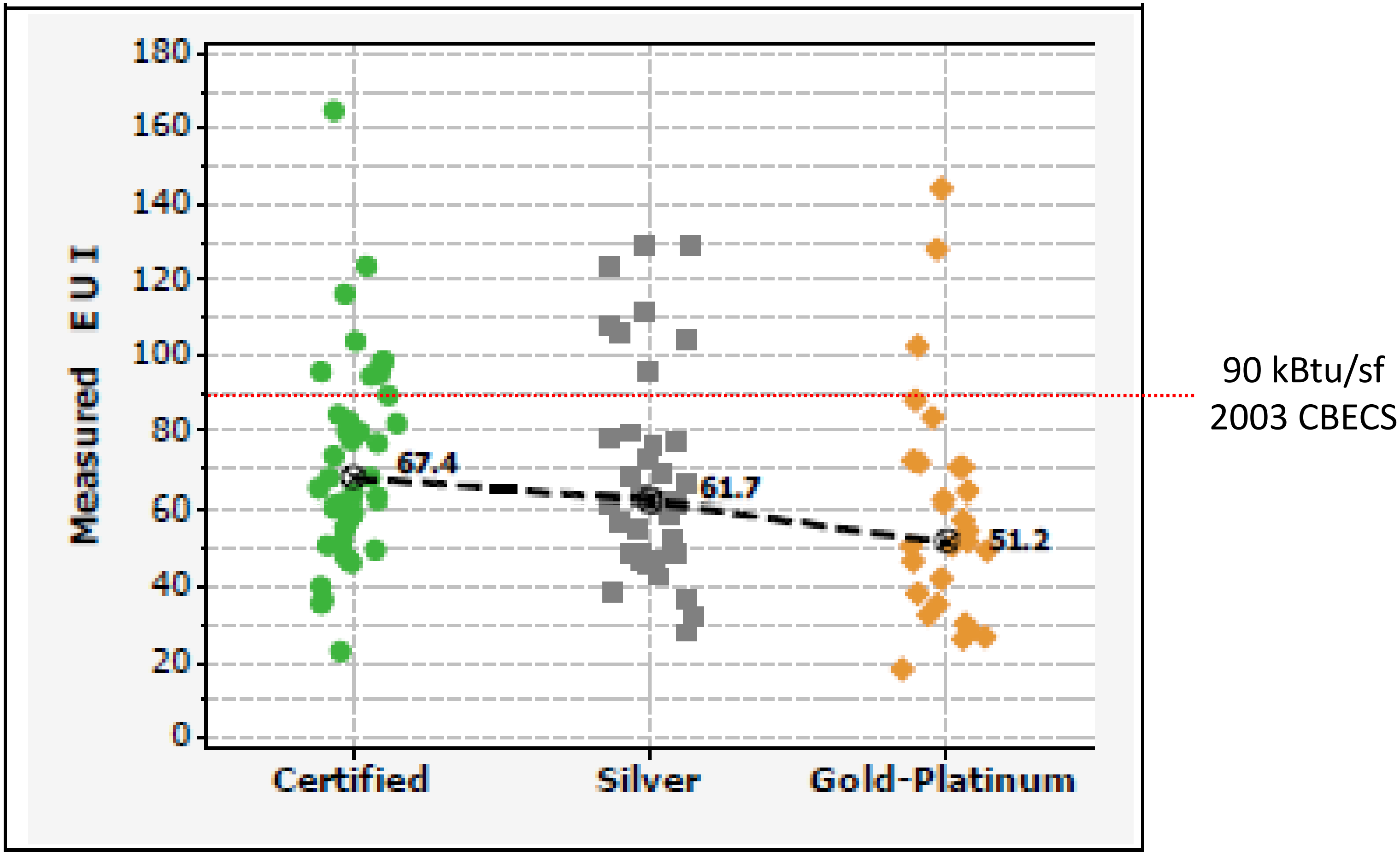
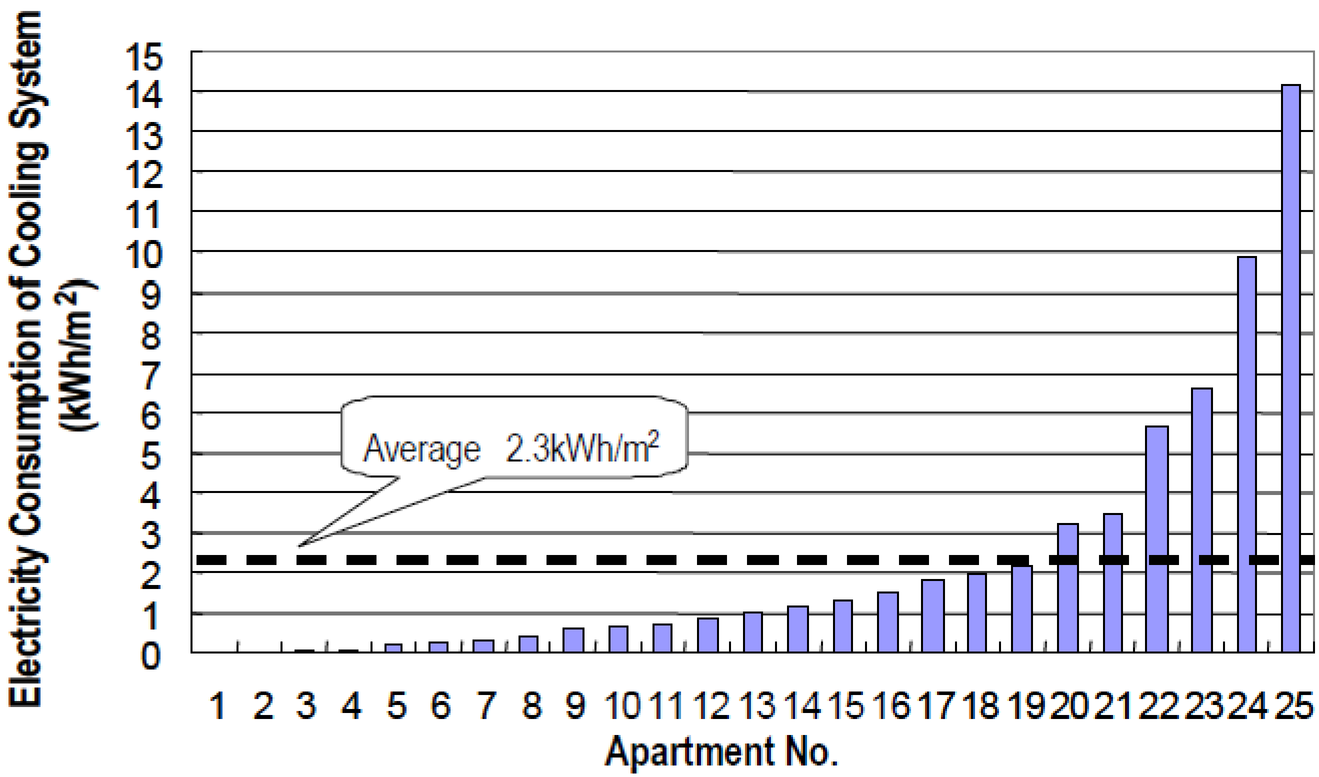


Figure 11: Measured EUIs (kBtu/sf) by LEED-NC Rating Level

Profile of Measured Energy Use of the 100 LEED-NC Certified Buildings
Source: Energy Performance of LEED® for New Construction Buildings, NBI, 2008

Measured Energy Performance (4)



Annual household electricity usage of split type air-conditioners in 2006, Beijing, China
Source: Y. Jiang & Q. Wei, Tsinghua University

Measured Energy Performance

Why such huge variations? Can building science and simulation community help explain?

- Age of buildings?
- Building designs and constructions?
- Climate?
- Operation and maintenance?
- Human behavior?
- Unknown, but *<u>can't be just measurement errors!</u>*

Measured Energy Performance

What can help us discover and understand the truth?

- Utility bills – monthly energy usage – not adequate
- Measured data with rational details and accuracy
  - Sub-metering
    - End uses (e.g. lighting, cooling, heating, plug-loads)
    - System level (e.g. HVAC systems)
    - Equipment/component level (e.g. chillers, boilers, elevators)
    - Floor/space level
    - Occupant level (per person)
  - Sub-hourly interval
  - Accuracy better than 2%
- Energy benchmarking, rating, and labeling
- **<u>Standardize energy monitoring and analysis platform</u>**

Example Developments

- USDOE - LBNL Energy Information System
- California commercial buildings monitoring network
- US/China Clean Energy Research Center on Building Energy Efficiency
- IEA Annex 53 Total Energy Use in Buildings
- ISO Standards

ASHRAE Standards & Guidelines

- ASHRAE Standard 105-2007, Standard Methods of Measuring, Expressing and Comparing Building Energy Performance
- ASHRAE Guideline 14-2002, Measurement of Energy and Demand Savings

IEA Annex 53

Total Energy Use in Buildings - Analysis and Evaluation Methods

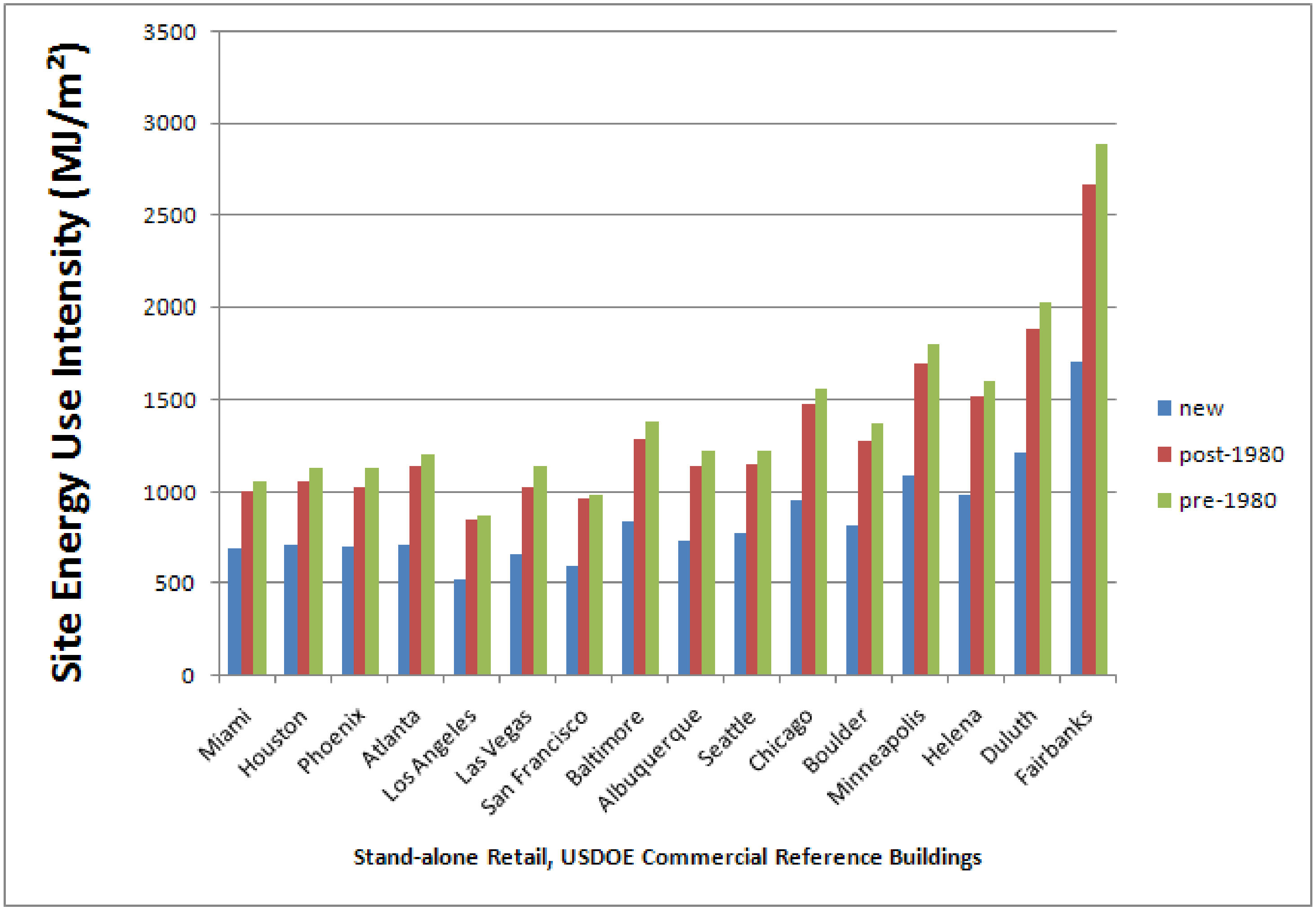
- Subtask A – Definition and Reporting
- Subtask B – Case Studies & Data Collection
- Subtask C – Statistical Analysis
- Subtask D – Energy Performance Evaluation

www.ecbcsa53.org

ISO Standards

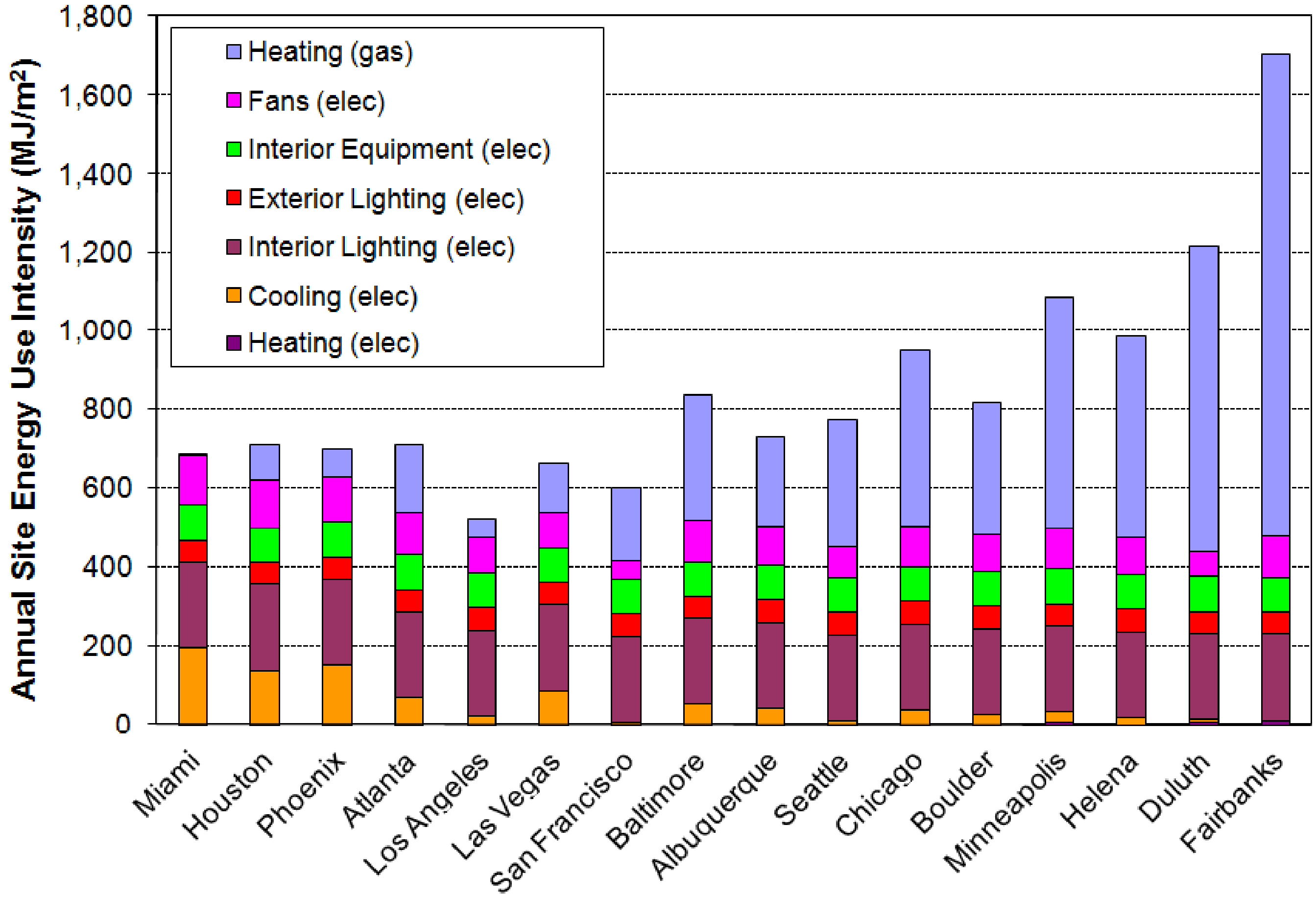
- ISO 16818 Building environment design -- Energy efficiency – Terminology
  - gives terms and definitions for use in the design of energy efficient buildings
- ISO 23045 Building environment design -- Guidelines to assess energy efficiency of new buildings
  - to assist designers/practitioners when collecting and providing the useful data that are required at different stages of the design process and to fulfill the definitions of the building as prepared by building designers.
- New standards under development by TC 205/163

Simulated Energy Performance (1)



Data Source: USDOE Commercial Reference Buildings

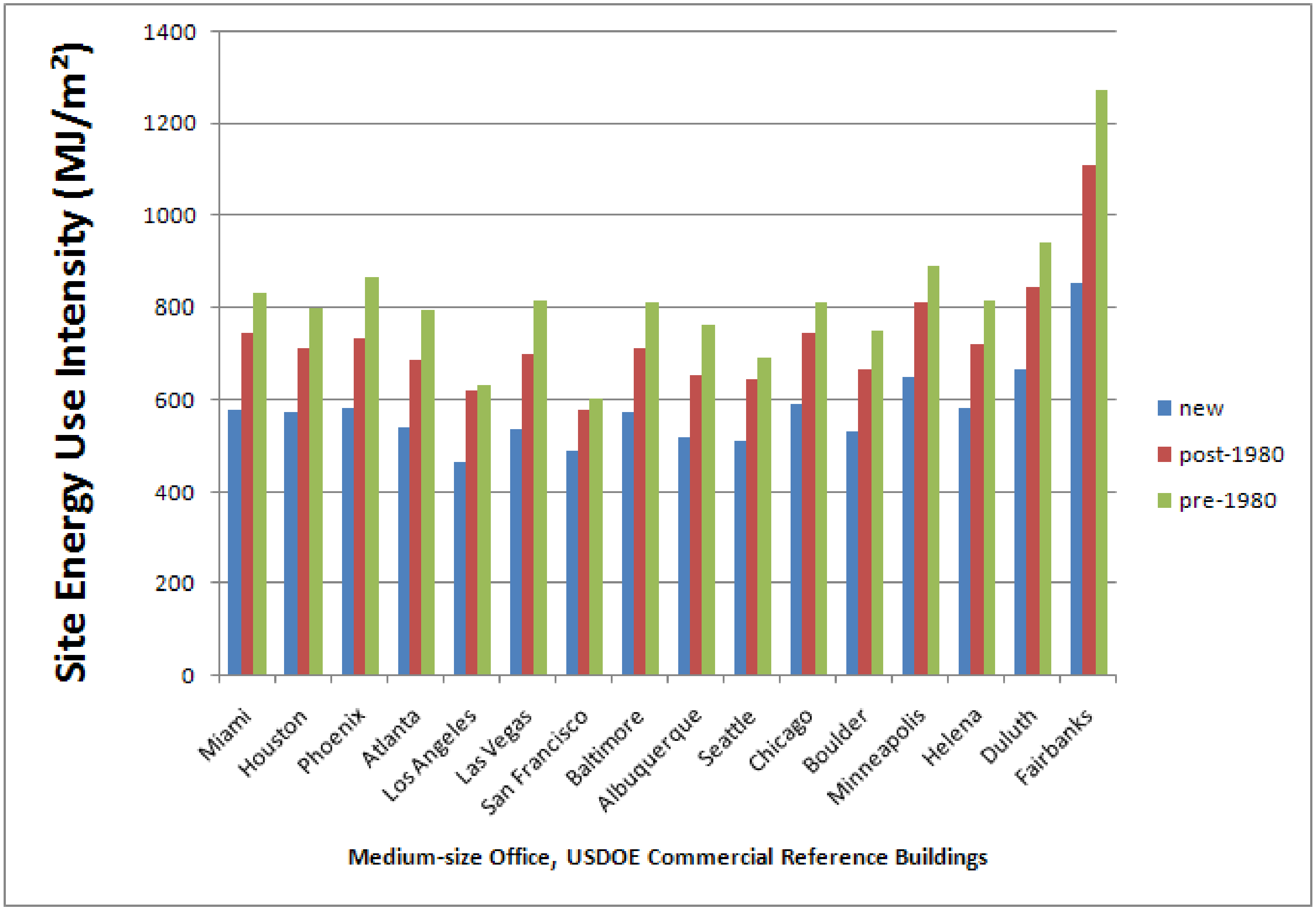
Simulated Energy Performance (1a)



Stand-alone Retail

Source: USDOE Commercial Reference Buildings – new (after 2004)

Simulated Energy Performance (2)



Data Source: USDOE Commercial Reference Buildings

Simulated Energy Performance

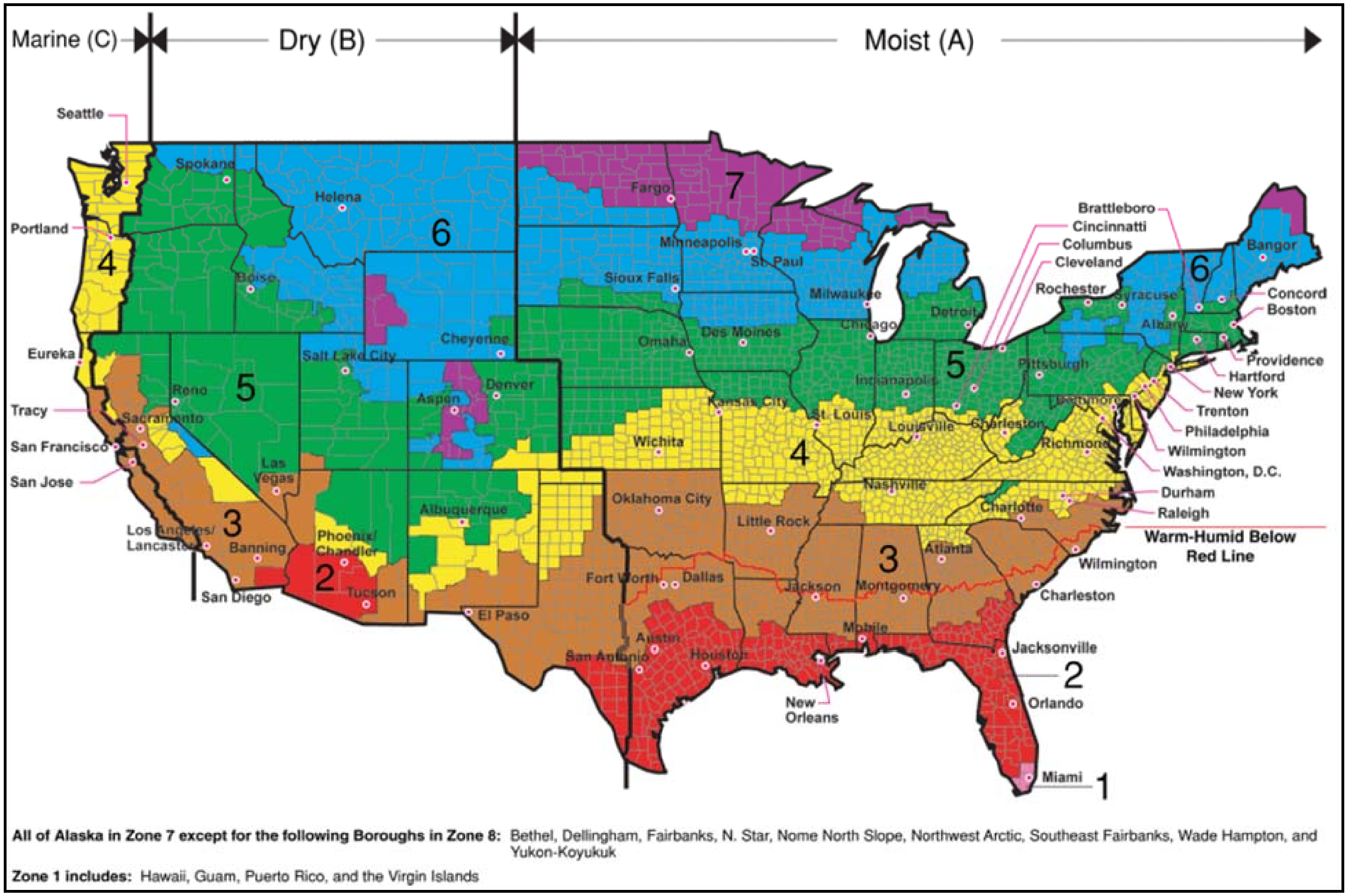
USDOE commercial reference buildings (CRBs)

– 16 building types
  covering 70% of the US commercial buildings
– 16 climates (from Miami to Fairbanks)
– 3 construction periods (pre-1980, post-1980, new)
– Based on CBECS, construction practice, code requirements
– Complete EnergyPlus models
– Developed by NREL/PNNL/LBNL

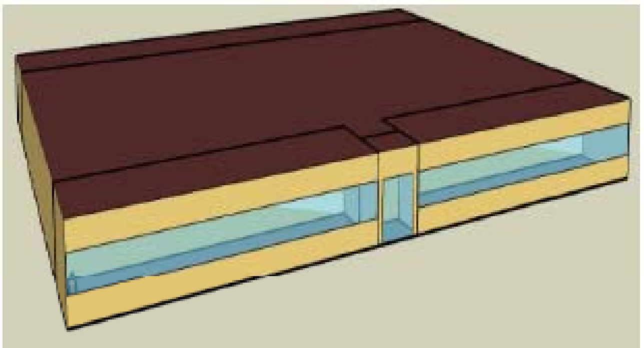
16 Building Types

	Building Activity	Area ft²	Floors	Source
Office	Small Office	5,500	1	Small Office AEDG
	Medium Office	53,630	3	2003 CBECS
	Large Office	498,588	12	2003 CBECS
School	Primary School	73,960	1	K-12 AEDG
	Secondary School	210,890	2	K-12 AEDG
Retail	Stand-alone Retail	24,962	1	2003 CBECS
	Strip Mall	22,500	1	2003 CBECS
	Supermarket	45,000	1	2003 CBECS
Food service	Quick Service Restaurant	2,500	1	2003 CBECS
	Full Service Restaurant	5,500	1	2003 CBECS
Lodging	Small Hotel	43,200	4	Highway Lodging AEDG
	Large Hotel	122,120	6	2003 CBECS
Health care	Hospital	241,351	5	2003 CBECS
	Outpatient health care	40,946	3	Health Care AEDG
Storage	Warehouse	52,045	1	Warehouse AEDG
Resi-dential	Midrise Apartment	33,740	4	PNNL

Climate Zones

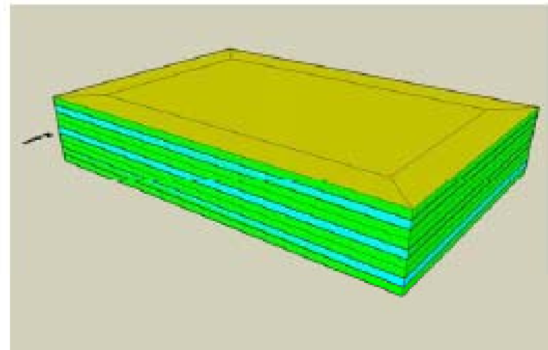


Two Selected Buildings



Floor area (ft²)	Number of Floors	Aspect Ratio	WWR
24,695	1	1.28	7%

Stand-alone Retail



Floor area (ft²)	Number of Floors	Aspect Ratio	WWR
53,600	3	1.5	33%

Medium-size Office

Now the Challenge

Measurement & Verification of energy use in completed commercial buildings tend to show large discrepancies between simulated and measured performance!

Energy Performance of Buildings Simulated vs. Measured (1)

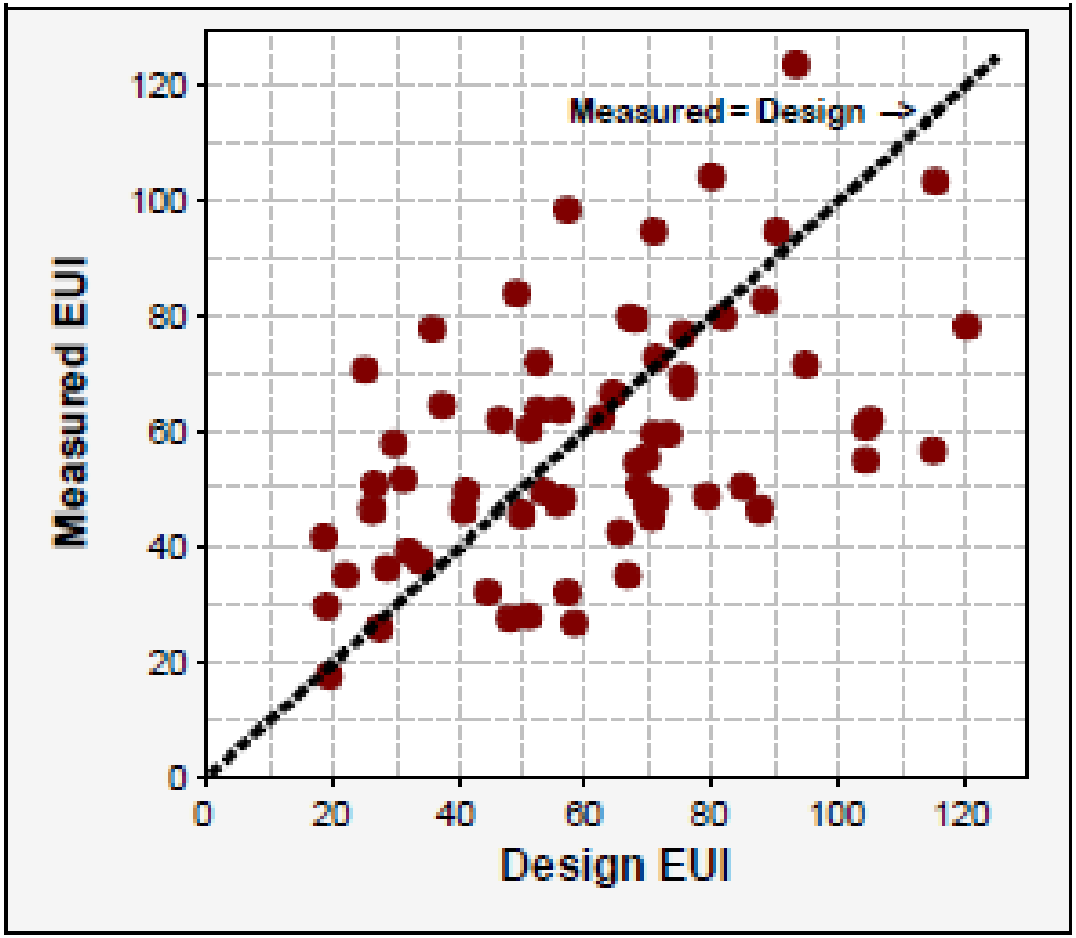


Figure ES- 4: Measured versus Design EUIs
All EUIs in kBtu/sf

Source: NBI Study 2008

Energy Performance of Buildings Simulated vs. Measured (2)

Table 8. Percent Discrepancy Comparison

Sites	Electric		CHW		HW		Total	
	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
Wisenbaker Engineering Resear Center (1999)	-27.3%	-31.2%	43.8%	49.0%	97.8%	93.9%	32.3%	33.9%
Wisenbaker Engineering Resear Center (2004)	-33.3%	-37.3%	33.2%	39.4%	95.4%	85.6%	18.8%	20.6%
Harrington Tower	10.6%	-7.6%	-35.6%	-87.2%	85.3%	-97.9%	-2.4%	-48.2%
Wehner Business Administration Building	-73.4%	-42.7%	-25.7%	-77.4%	86.9%	64.6%	-41.0%	-33.0%
John B. Connally Building	-15.0%	-16.3%	N/A	N/A	N/A	N/A	-15.0%	-16.0%

Negative numbers mean over-predict, positive for under-predict
Texas A&M, used DOE-2.1E

Mushtaq Ahmad, Charles H. Culp, Uncalibrated Building Energy Simulation Modeling Results, ASHRAE HVAC&R Research, Vol. 12, No. 4, October 2006

Energy Performance of Buildings
Simulated vs. Measured

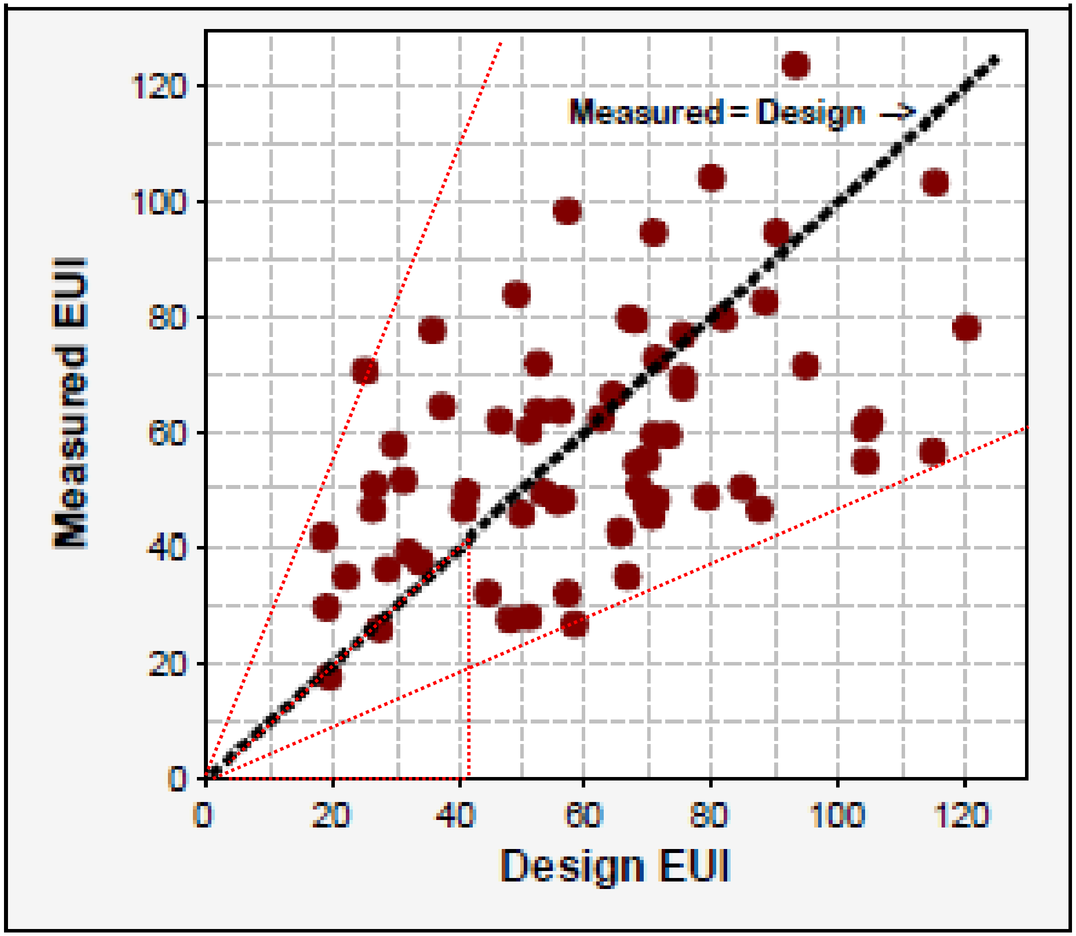


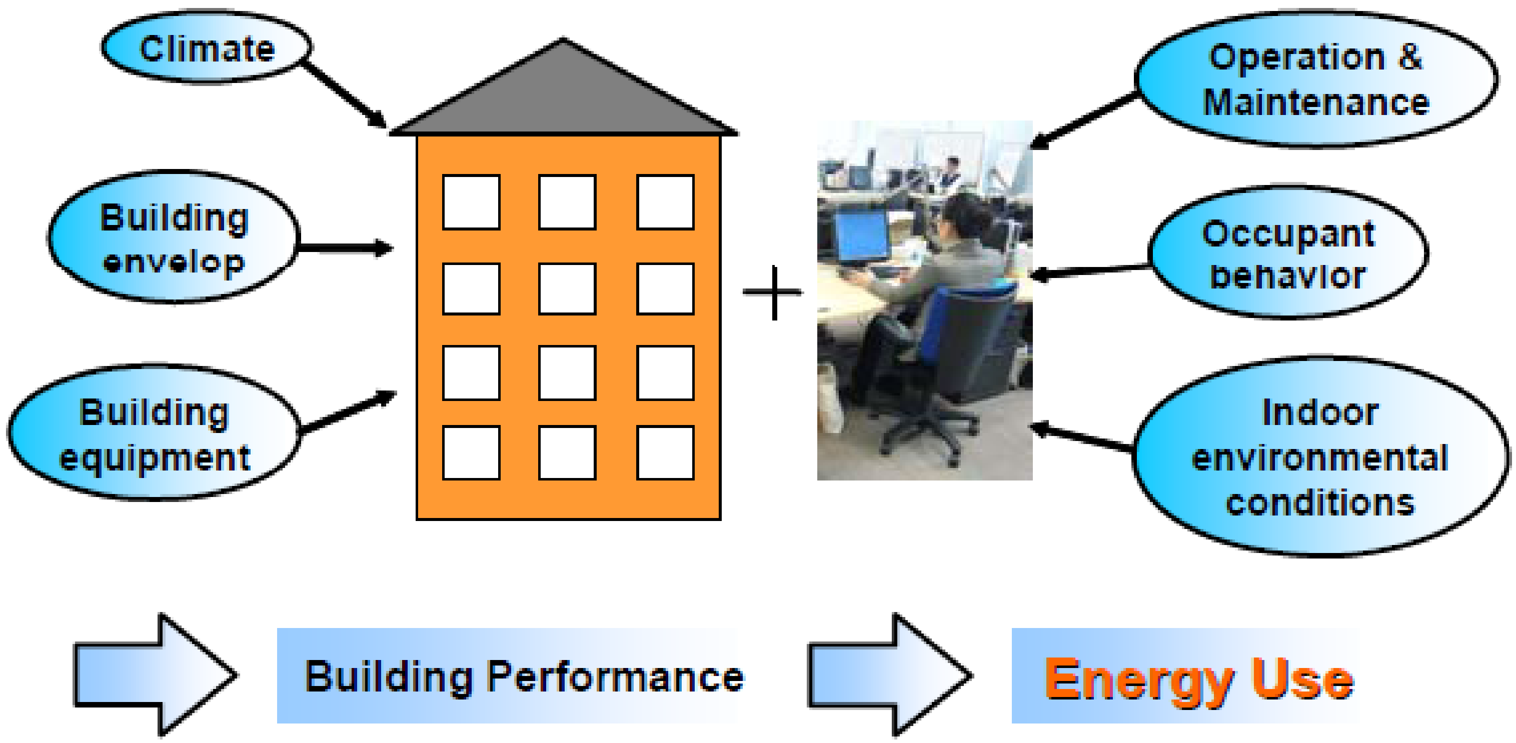
Figure ES- 4: Measured versus Design EUIs
All EUIs in kBtu/sf

Source: NBI Study 2008

A few facts:

1. Various building types, ages, locations
2. Average over all projects not bad
3. Max over-predict by **120%**
4. Max under-predict by **65%**
5. **Almost all under-predict for low energy designs** (red triangle: EUI <= 40)
6. Uncalibrated simulated results

Driving Factors of Building Energy Performance



Source: IEA Annex 53
Total Energy Use in Buildings - Analysis and Evaluation Methods

Analysis of Discrepancies (1)

Back to Basics – Energy simulations done for LEED projects were not to predict actual energy use of buildings

Majority of simulations are done to:

- Evaluate and compare design alternatives
- Calculate relative performance to certain baselines (Title 24, ASHRAE 90.1, 189.1, LEED, etc.)
- Code compliance, but
- Not to predict actual energy use/cost

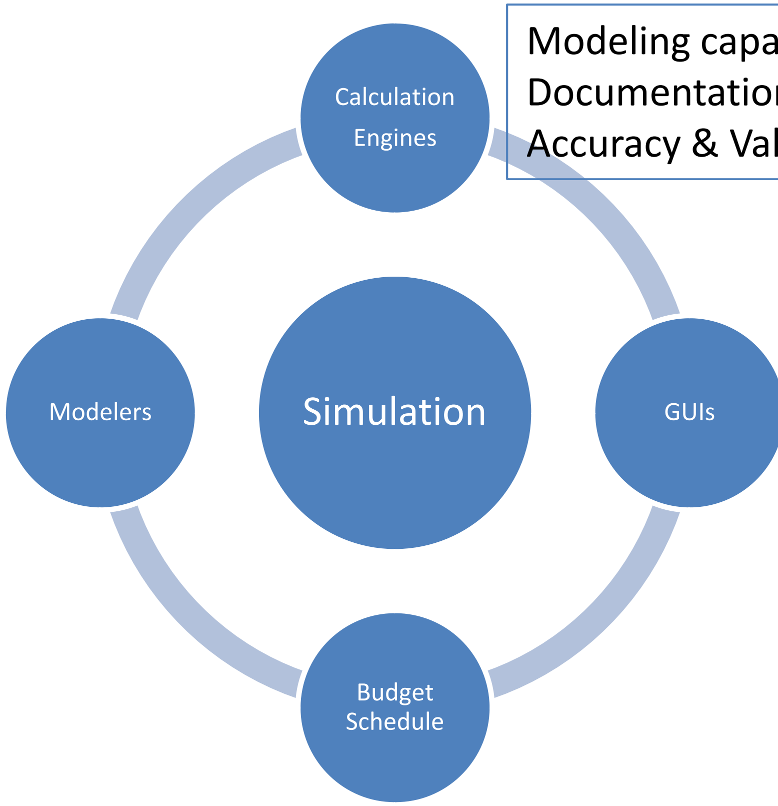
With significant extra dedicated effort simulations can predict actual energy consumption within a reasonable range

Analysis of Discrepancies (2)

	Measurement	Simulation
Building & Systems	As-built	As-designed?
Operation & controls	With problems	Perfect w/o problems
Human behavior	Actual	Simplified too much
Equipment performance	Actual performance with faults & degradation	Assumed default performance w/o faults or degradation
Weather data	On-site	TMY2/TMY3
Internal loads	Actual	Assumed
Energy uses	All included	Some misc uses may not be included
New innovative systems		Cannot be modeled. Ad-hoc work-around
Consistency of accuracy	Very good	Very bad
Quality controls		Not adequate

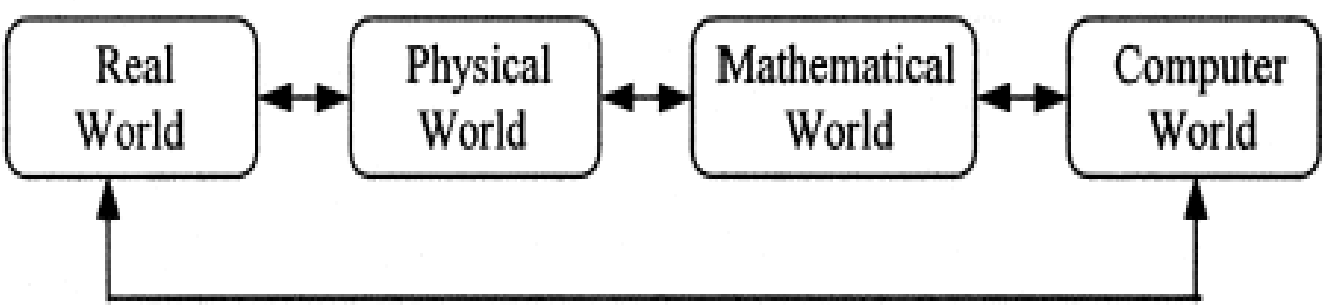
Complexity of Simulation

Modeling capability & limitations
Documentation & source code
Accuracy & Validation



Education
Experience
Training

Ease of use
Interoperability
Parametric runs
Reporting



Case Study - Data Centers

How does EnergyPlus compare to DOE-2.2?

- Data centers with air-cooled DX cooling
- With and without air-side economizer
- Four climate zones – San Francisco, Miami, Chicago, and Phoenix
- Use EnergyPlus v2.1 and DOE-2.2 v45
- What are surprises and how to address them

Air-Cooled DX Coil Models

User Inputs	DOE-2.2 DX Coil	EnergyPlus DX Coil
Under ARI rated conditions: Outdoor dry-bulb 95°F, entering dry-bulb 80°F and wet-bulb 67°F.		
Rated Cooling Efficiency	Yes. EIR = 1 / COP	Yes. COP
Rated Total Cooling Capacity	Yes	Yes
Rated Sensible Cooling Capacity	Yes	No
Rated Sensible Heat Ratio	No	Yes
Rated Bypass Factor	Yes	No
Rated Air Flow Rate	Yes	Yes
Curves to describe DX coil operating performance under non-rated and part-load conditions		
Cool-Cap-fEWB&OAT (Total cooling capacity as a function of entering wet-bulb and outdoor air dry-bulb temperatures)	Yes	Yes
Sens-Cap-fEWB&OAT (Sensible cooling capacity as a function of entering wet-bulb and outdoor air dry-bulb temperatures)	Yes	No
Cool-EIR-fEWB&OAT (Cooling efficiency as a function of entering wet-bulb and outdoor air dry-bulb temperatures)	Yes	Yes
Cool-EIR-fPLR (Cooling efficiency as a function of part-load ratio)	Yes	Yes
Bypass-Factor-fAirFlow (Bypass factor as a function of air flow ratio)	Yes	No
Bypass-Factor-fEWB&EDB (Bypass factor as a function of entering wet-bulb and dry-bulb temperatures)	Yes	No

Results – San Francisco

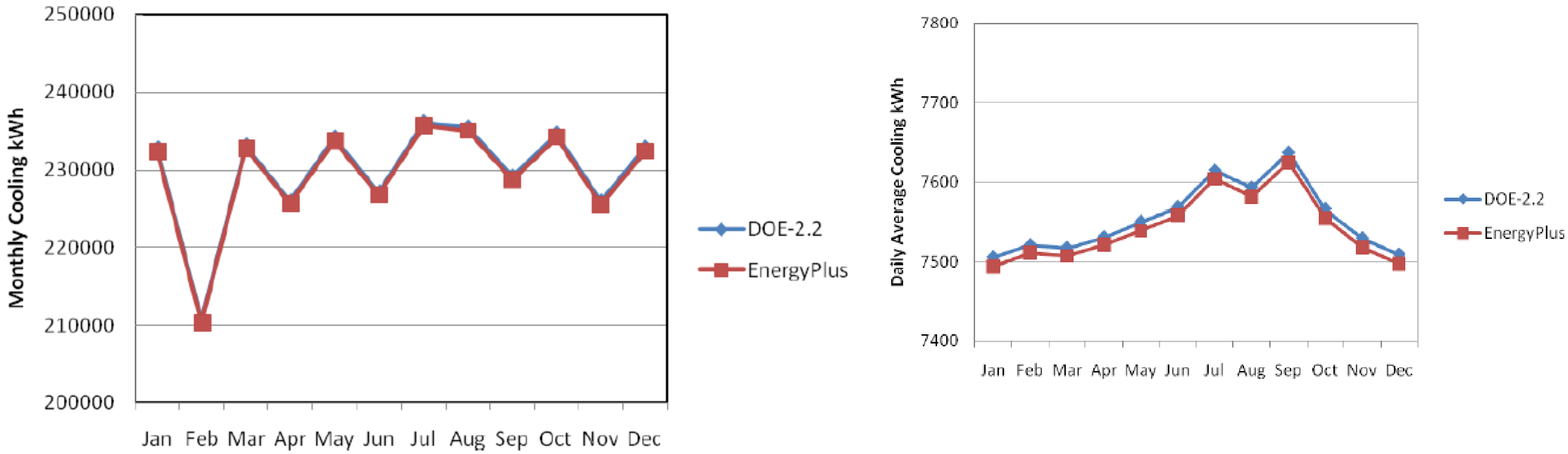


Figure 1 – Monthly Cooling Electricity Consumption for San Francisco Runs without Air Economizer

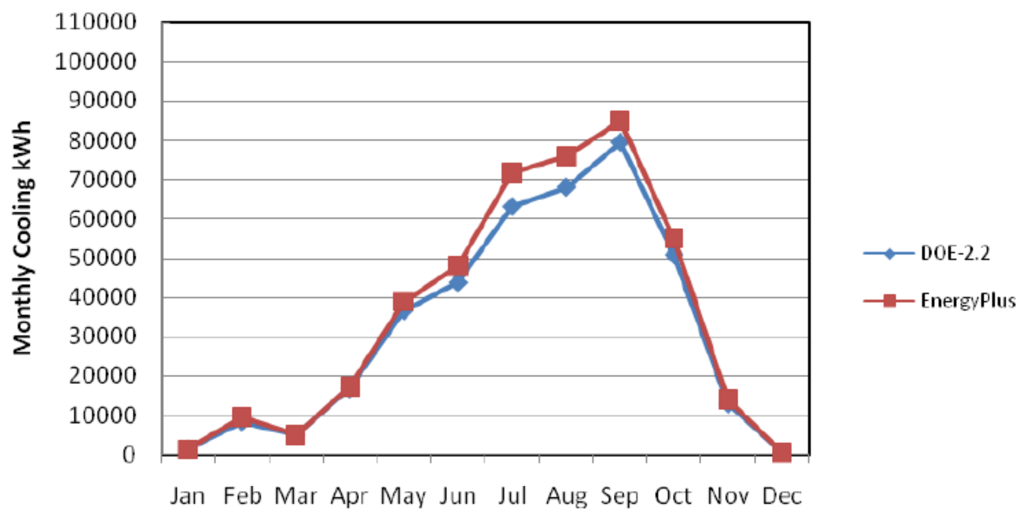


Figure 2 – Monthly Cooling Electricity Consumption for San Francisco Runs with Air Economizer

Results - Chicago

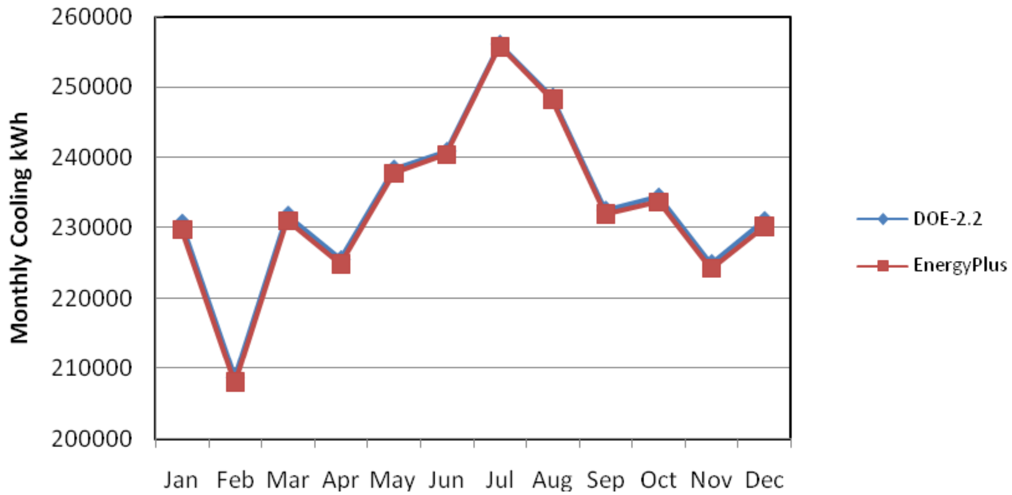


Figure 1 – Monthly Cooling Electricity Consumption for Chicago Runs without Air Economizer

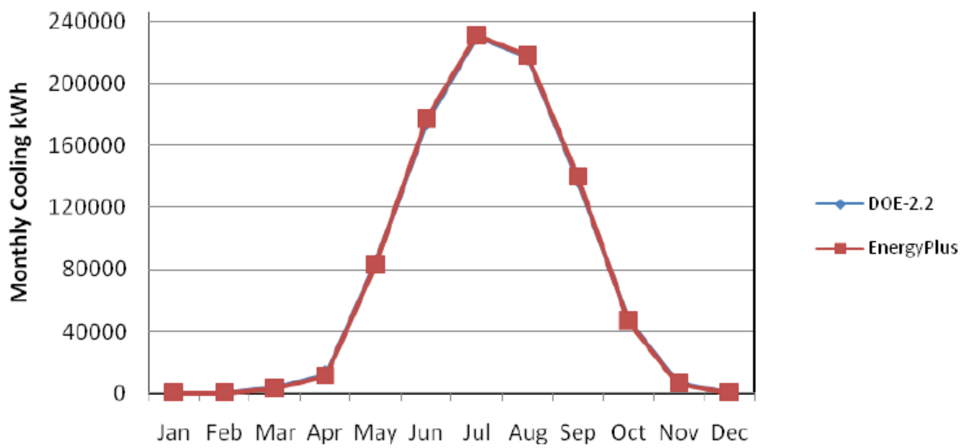


Figure 6 – Monthly Cooling Electricity Consumption for Chicago Runs with Air Economizer

Summary of Findings

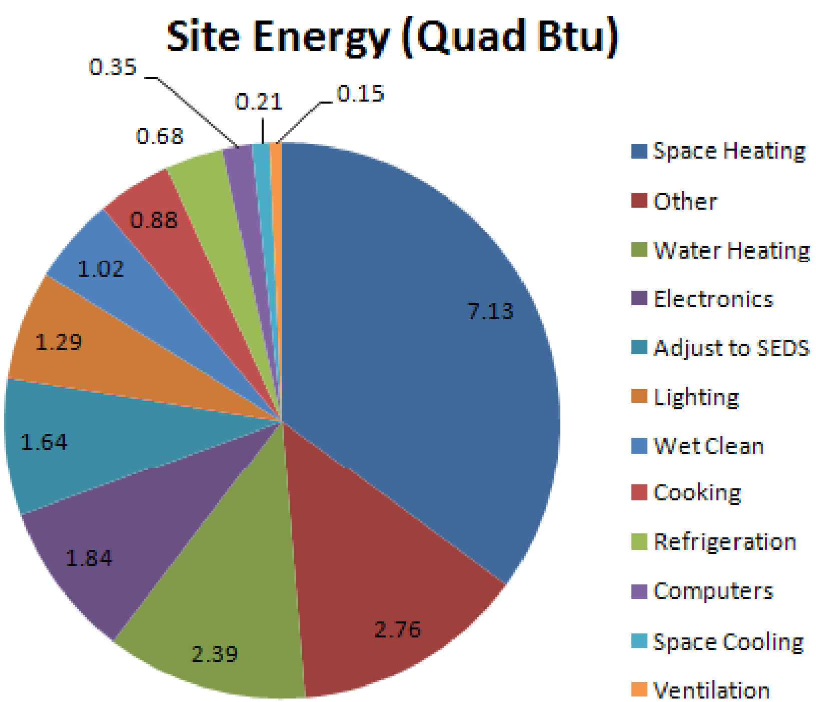
EnergyPlus and DOE-2.2 can produce close results if:

- Use same/equivalent equipment size, efficiency, and performance curves
- Use same operating schedules and internal loads
- Use same weather data
- Pay attention to DOE-2 defaults

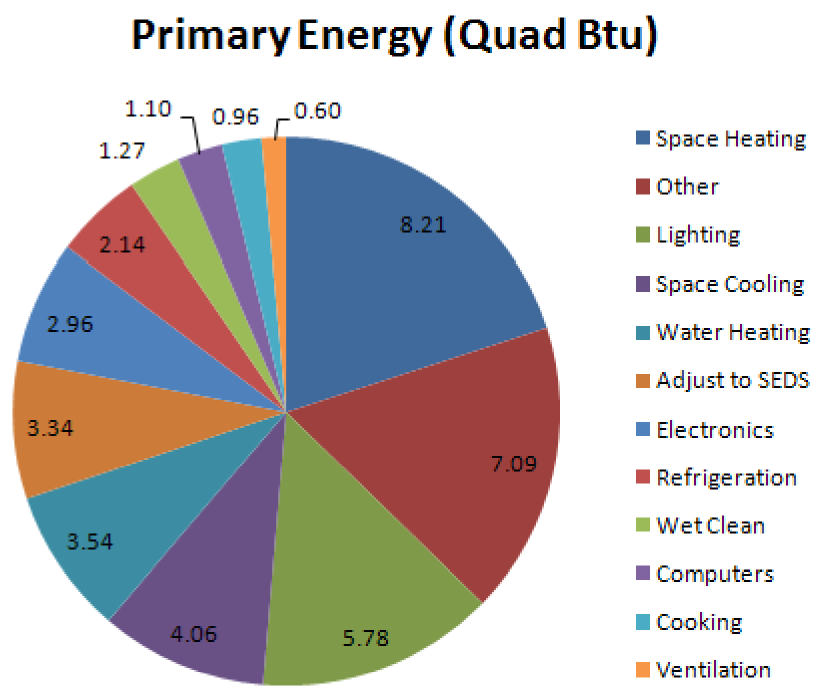
Case Study - Space Heating Energy Use of Office Buildings

- Space heating is the largest end-use
- Office buildings are the most common building type in US commercial stocks
- Long complaints from the simulation community about simulations under-predicting space heating energy use
- Understand key factors

U.S. Buildings Energy End-Use Splits



Total: 20.33



Total: 41.04

Data Source: USDOE 2010 Buildings Energy Databook

Methodology

- Simulations with EnergyPlus Version 6
- Use the large and small-size office buildings from USDOE CRBs
- 4 Climates: San Francisco, Chicago, Minneapolis, Fairbanks
- Select a few parameters that have the most potential impact on space heating
- Benchmark with data from CBECS, CEUS, HPB

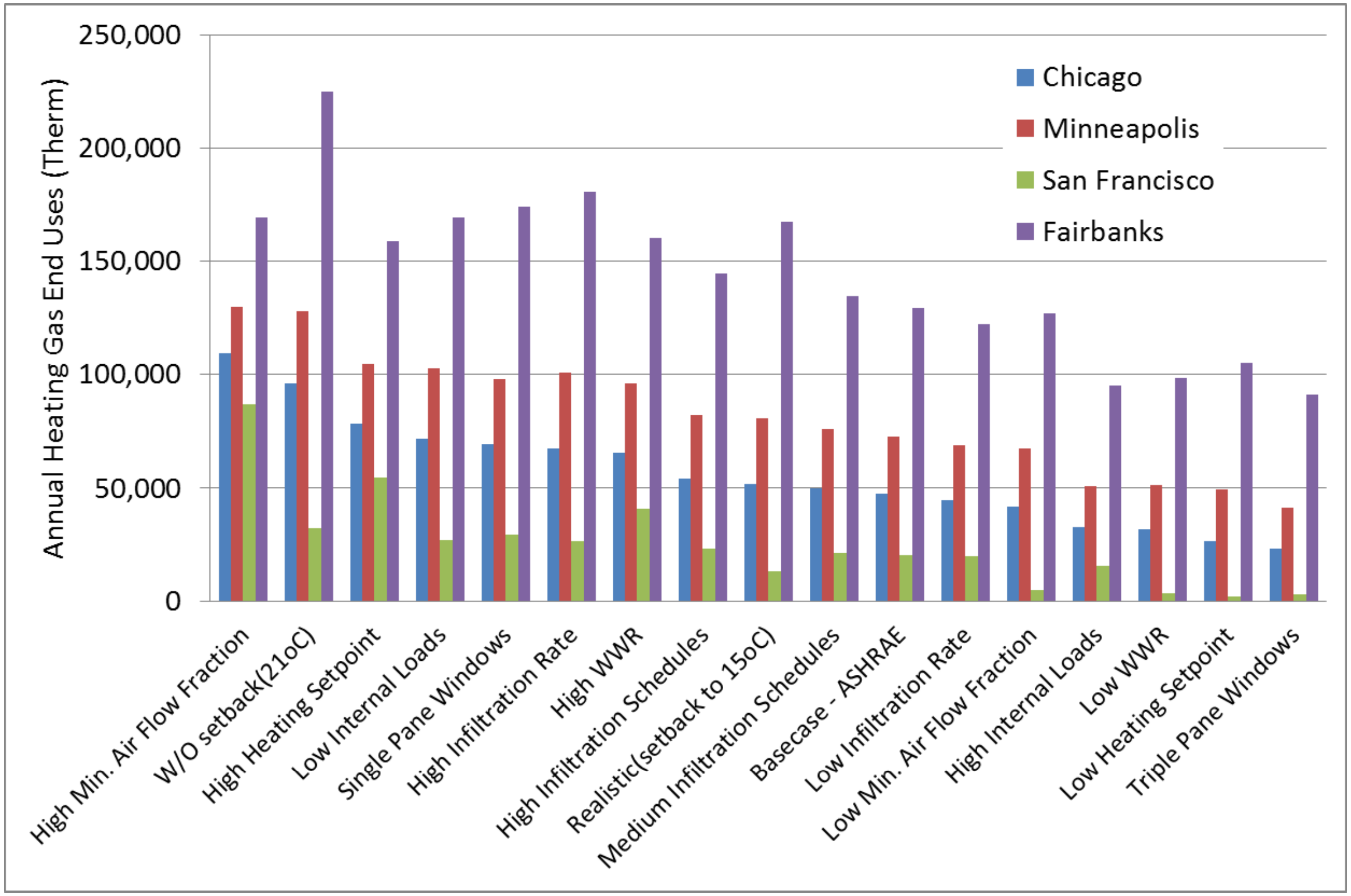
Key Parameters (1)

Description	LPD (W/m^2)	EPD (W/m^2)	WWR (Large/Small Office)	INF ($m^3/s-m^2$) (ach)	INFSCH	MAFF (Large Office)	Heating setpoint (°C)	Thermostat Setback (°C)
Basecase	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	21	10
High Internal Loads (50% higher)	16.14	16.14	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	21	10
Low Internal Loads (50% lower)	5.38	5.38	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	21	10
High WWR	10.76	10.76	0.68/0.4	0.000302 (0.65 ach)	0.25	0.3	21	10
Low WWR	10.76	10.76	0.1/0.1	0.000302 (0.65 ach)	0.25	0.3	21	10
High Infiltration Rate (105% higher)	10.76	10.76	0.4/0.2	0.001133 (2.44ach)	0.25	0.3	21	10
Low Infiltration Rate (50% lower)	10.76	10.76	0.4/0.2	0.000189 (0.407 ach)	0.25	0.3	21	10
High Infiltration	10.76	10.76	0.4/0.2	0.000302 (0.65	1	0.3	21	10
Medium Infiltration Schedules	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.5	0.3	21	10
High Minimum Air Flow Fraction (Large office)	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.5	21	10
Low Minimum Air Flow Fraction (Large office)	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.15	21	10

Key Parameters (2)

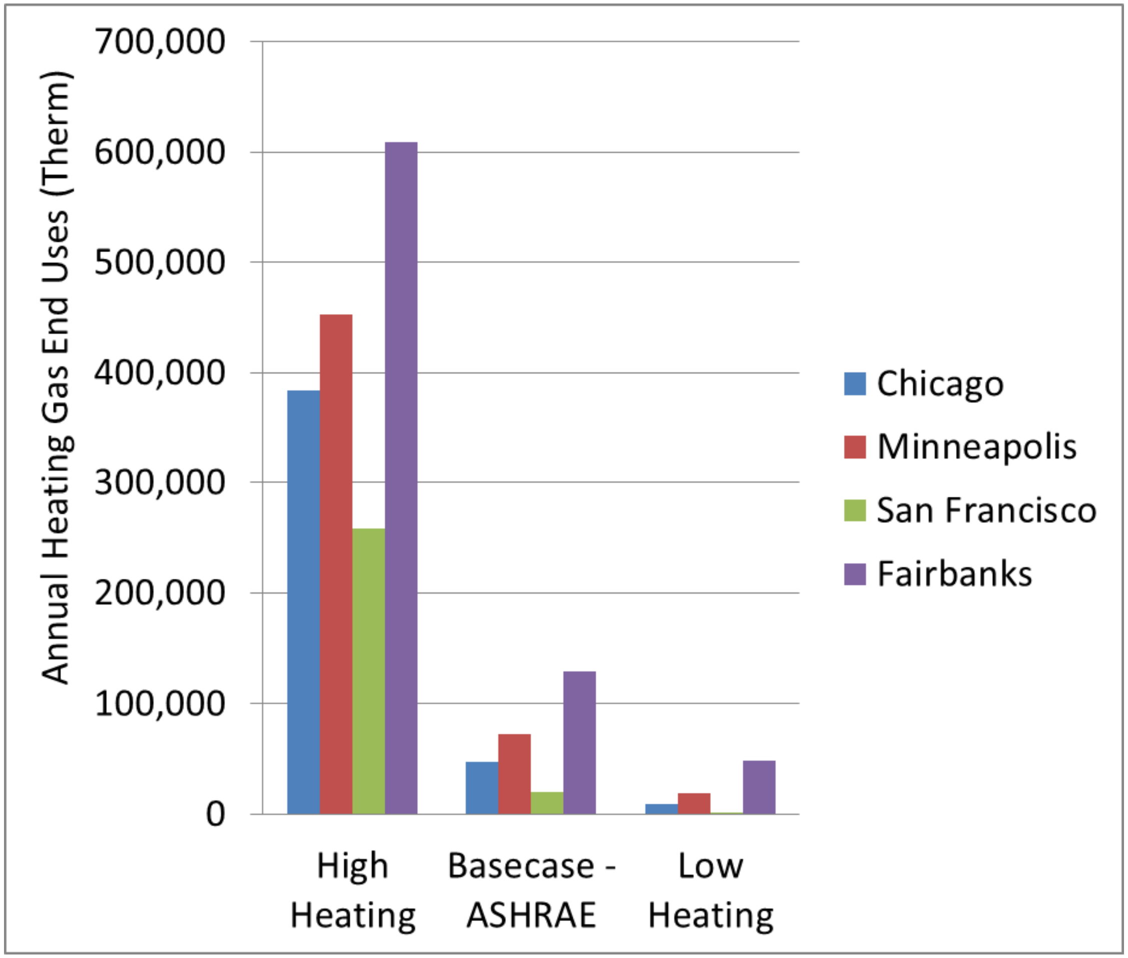
Description	LPD (W/m^2)	EPD (W/m^2)	WWR (Large/Small Office)	INF ($m^3/s\text{-}m^2$) (ach)	INFSCH	MAFF (Large Office)	Heating setpoint (°C)	Thermostat Setback (°C)
Basecase	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	21	10
High Heating Setpoint	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	23	10
Low Heating Setpoint	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	18	10
Single Pane Windows	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	21	10
Triple Pane Windows	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	21	10
Thermostat setback to15°C	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	21	15
Thermostat no setback	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	21	21
Wall/roof pre-1980	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	21	10
Wall/roof post-1980	10.76	10.76	0.4/0.2	0.000302 (0.65 ach)	0.25	0.3	21	10
High Heating	5.38	5.38	0.68/0.4	0.000604 (1.3 ach)	1	0.5	23	15
Low Heating	16.14	16.14	0.1/0.1	0.000151 (0.326 ach)	0.25	0.15	18	10

Results (1)



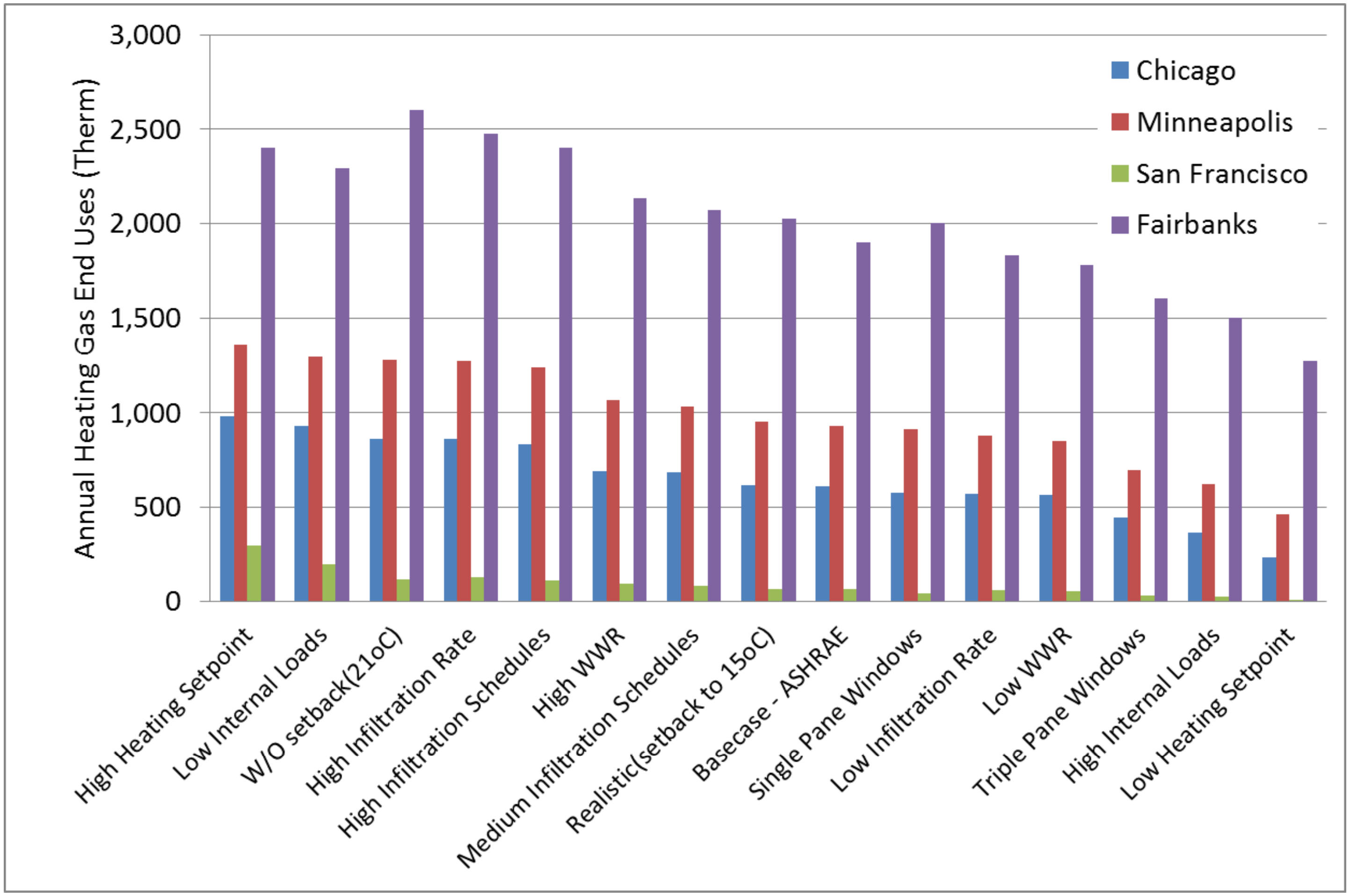
Space heating energy use of the large office building

Results (2)



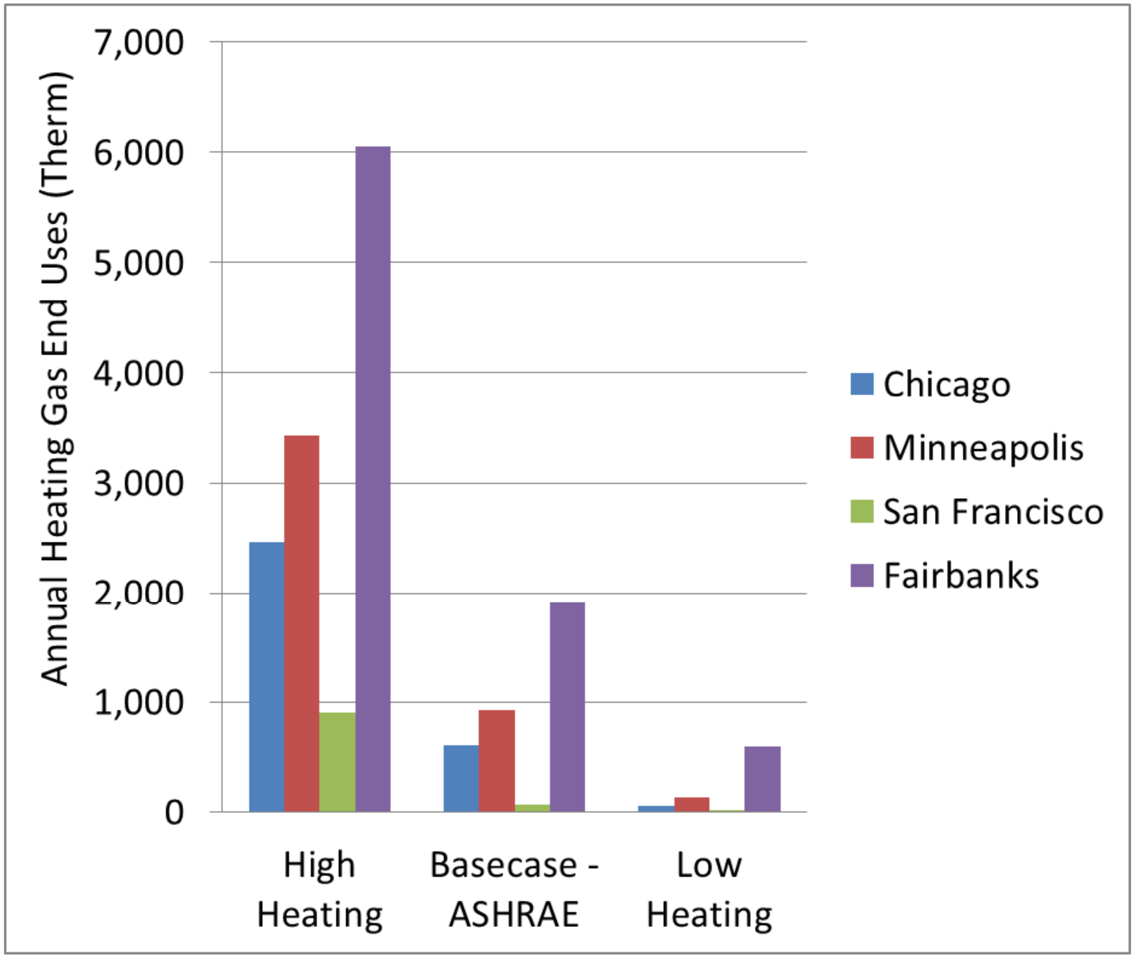
Space heating energy use of the large office building

Results (3)



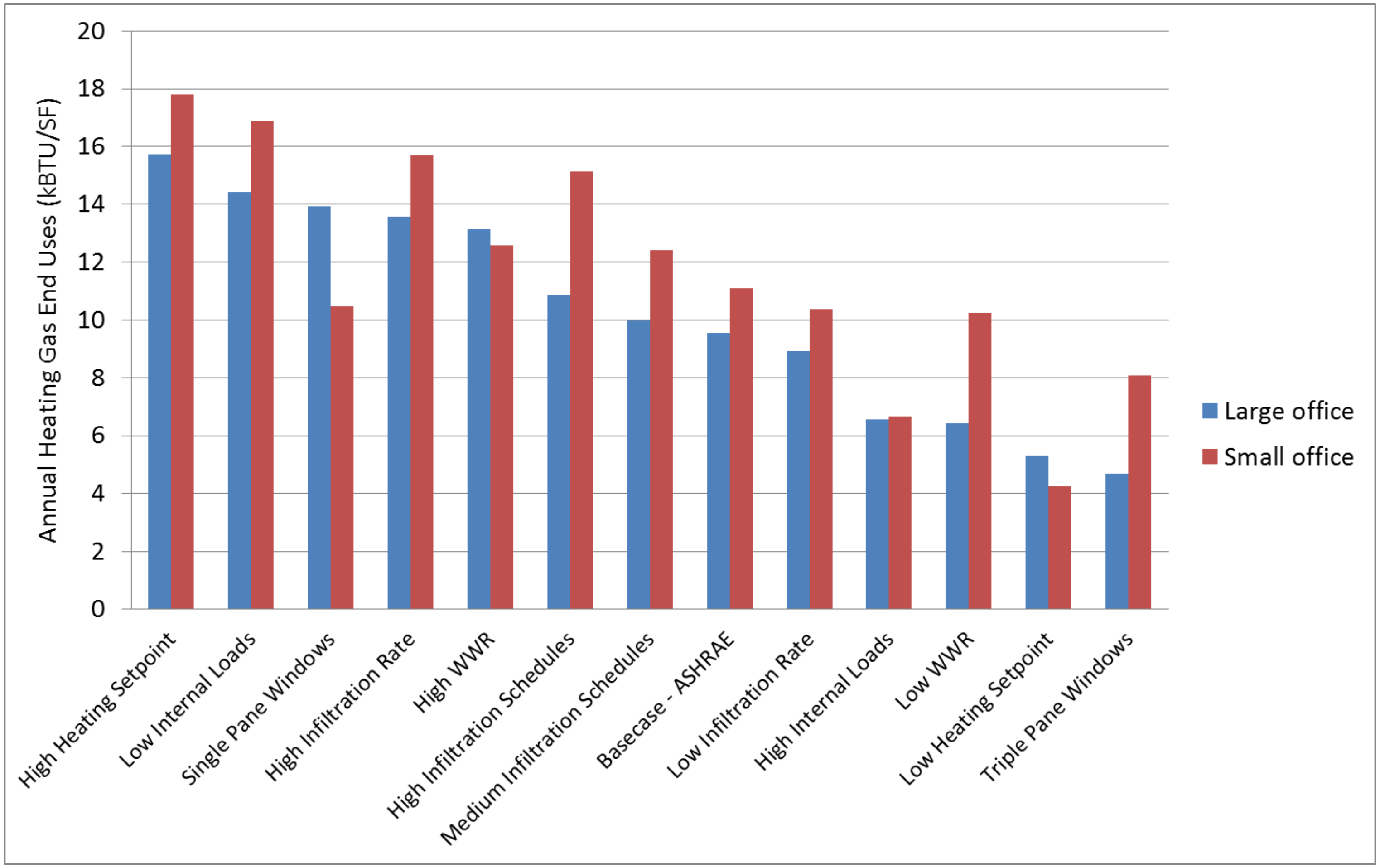
Space heating energy use of the small office building

Results (4)



Space heating energy use of the small office building

Results (5)

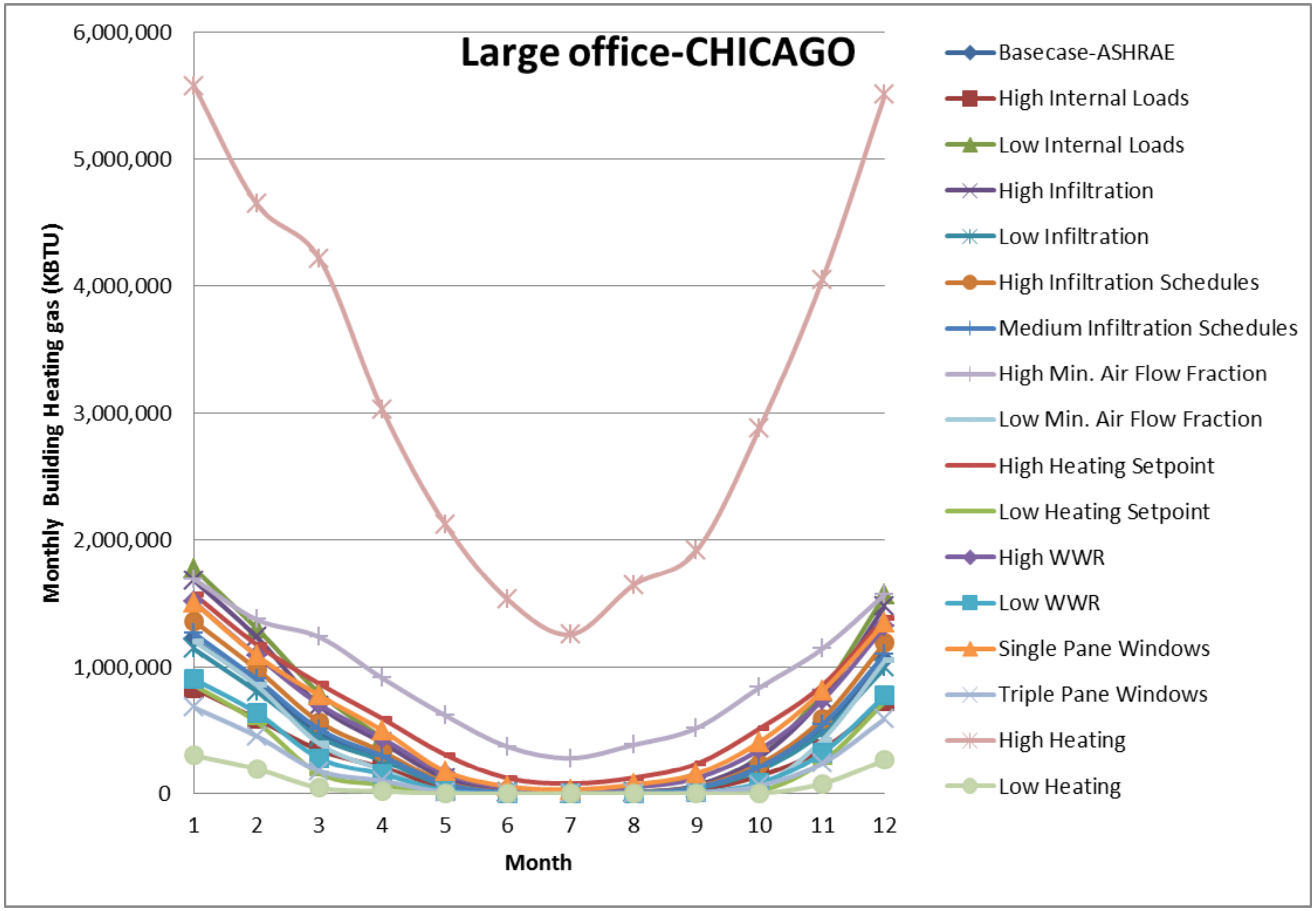


Space heating EUI in Chicago

Results (6)

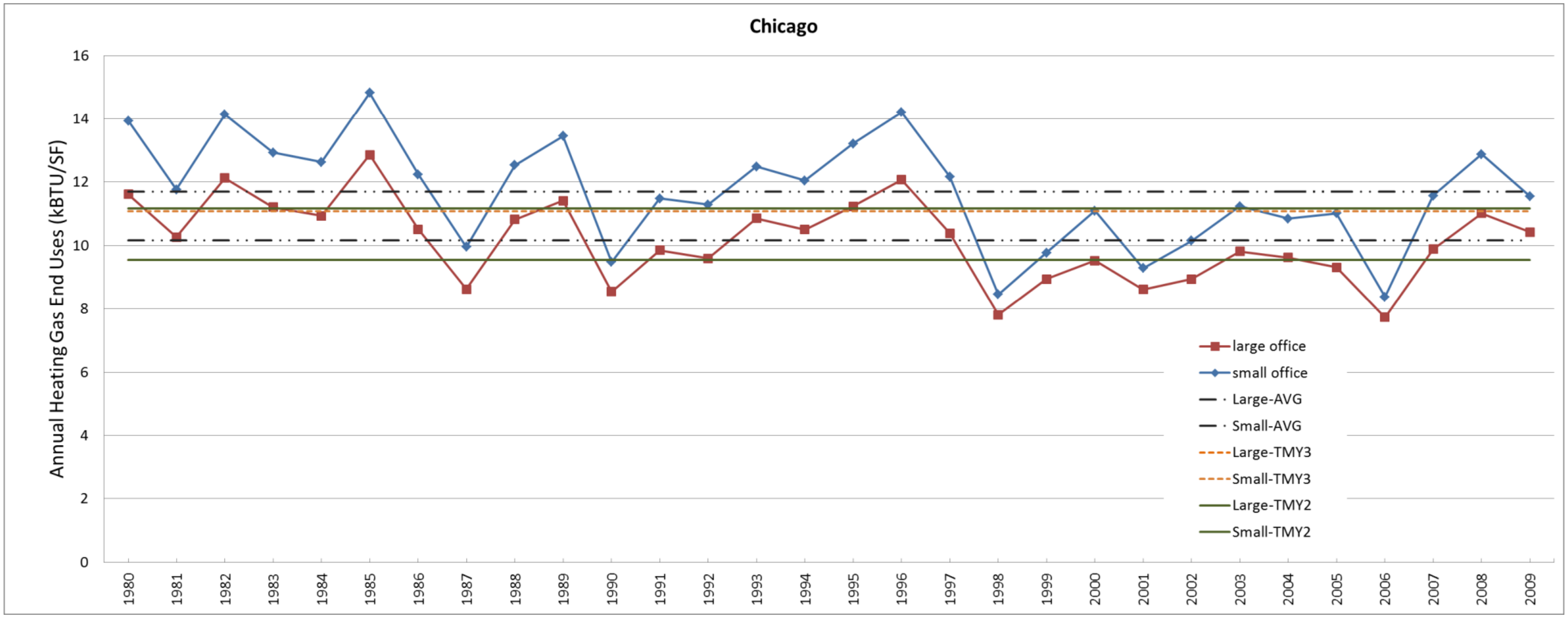
Space heating EUI at different building periods

Results (7)



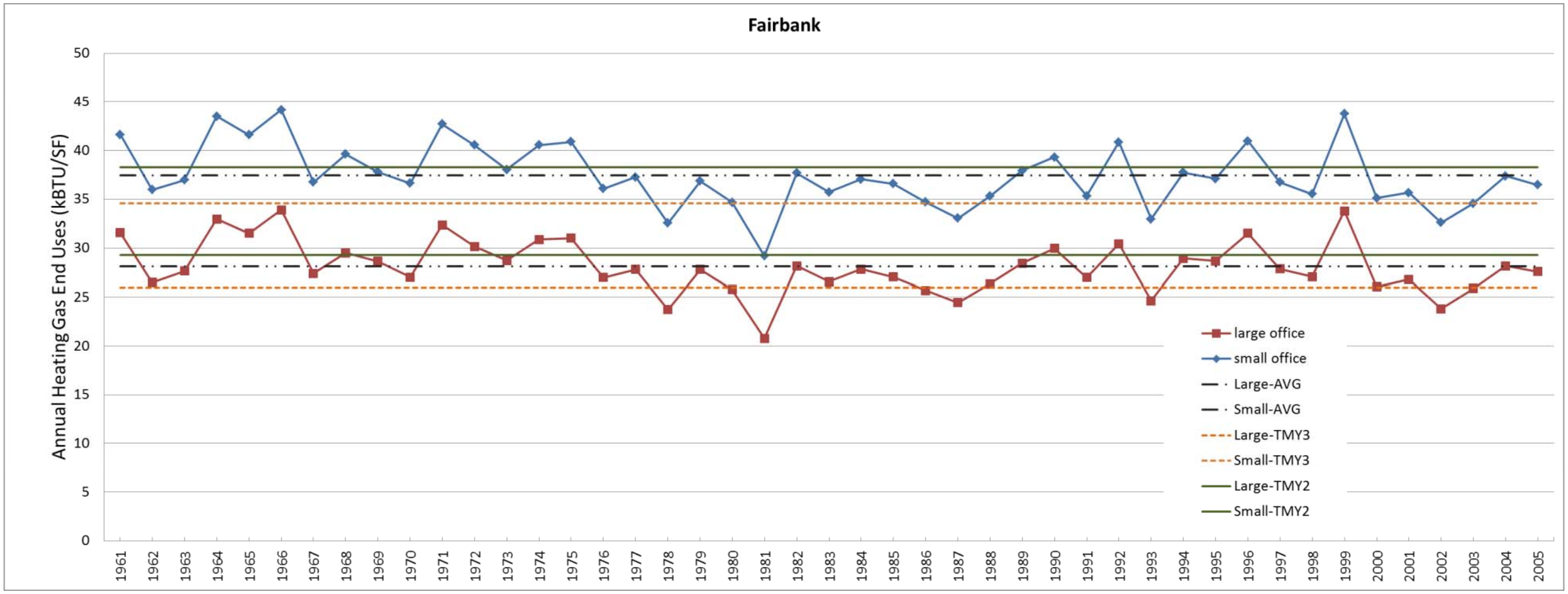
Monthly space heating gas use for the large office in Chicago

Results (8)



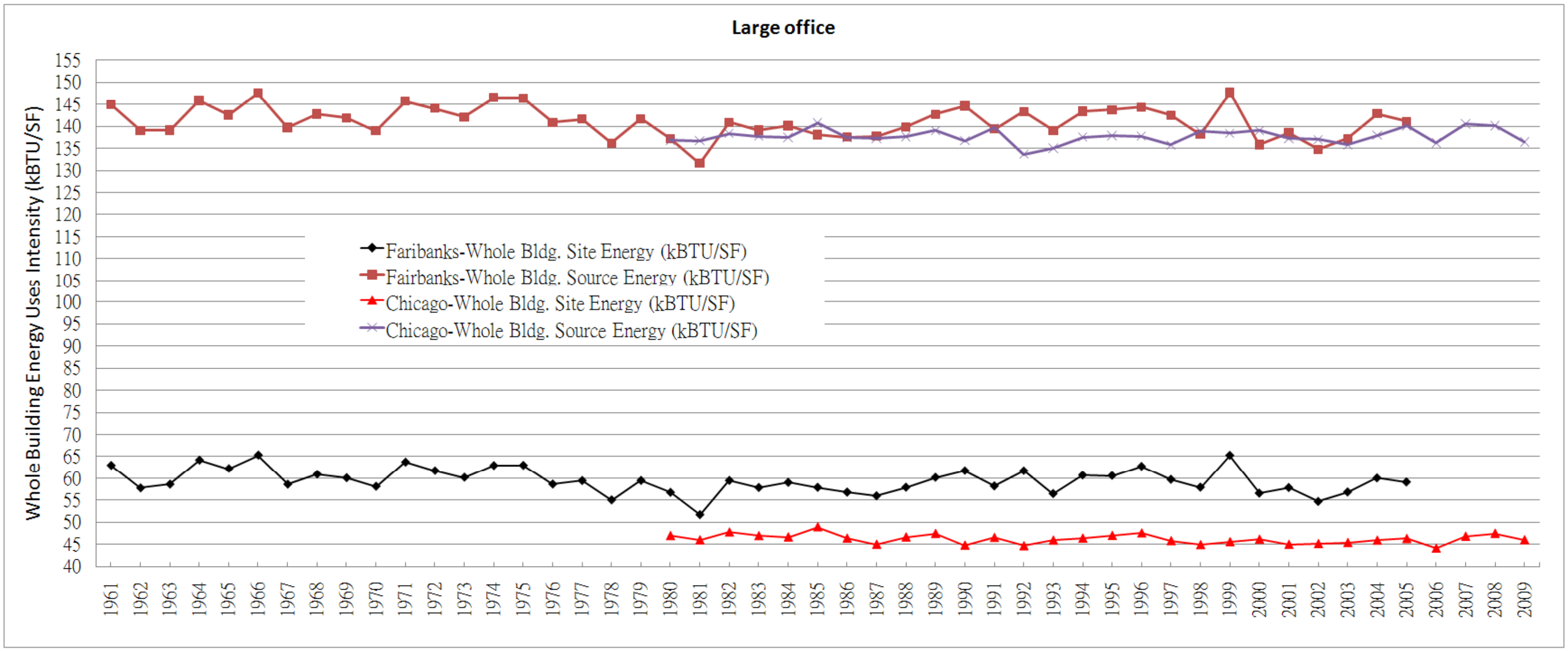
Space heating EUI, Chicago, 1980 to 2009

Results (9)



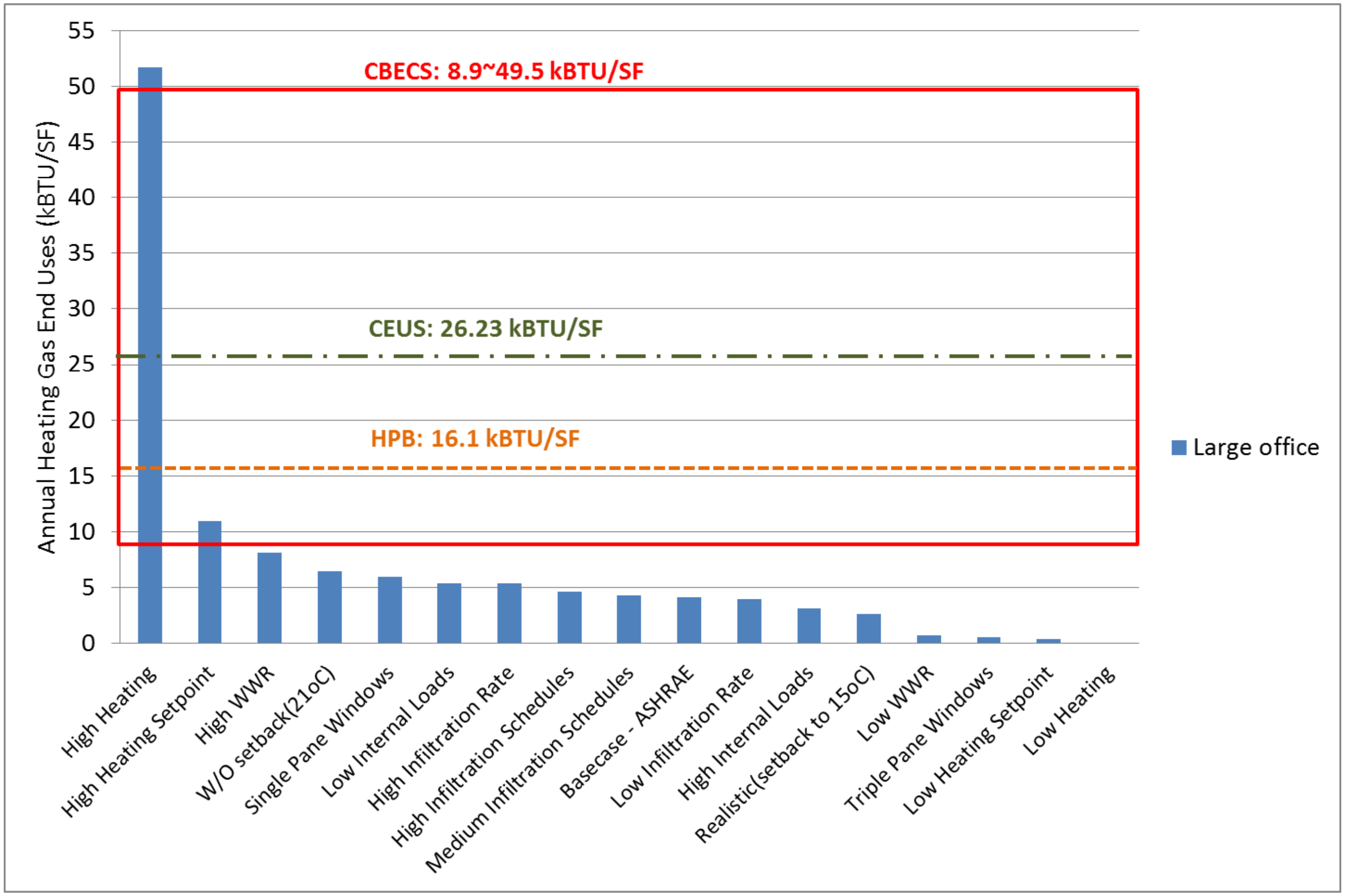
Space heating EUI, Fairbanks, 1961 to 2005

Results (10)



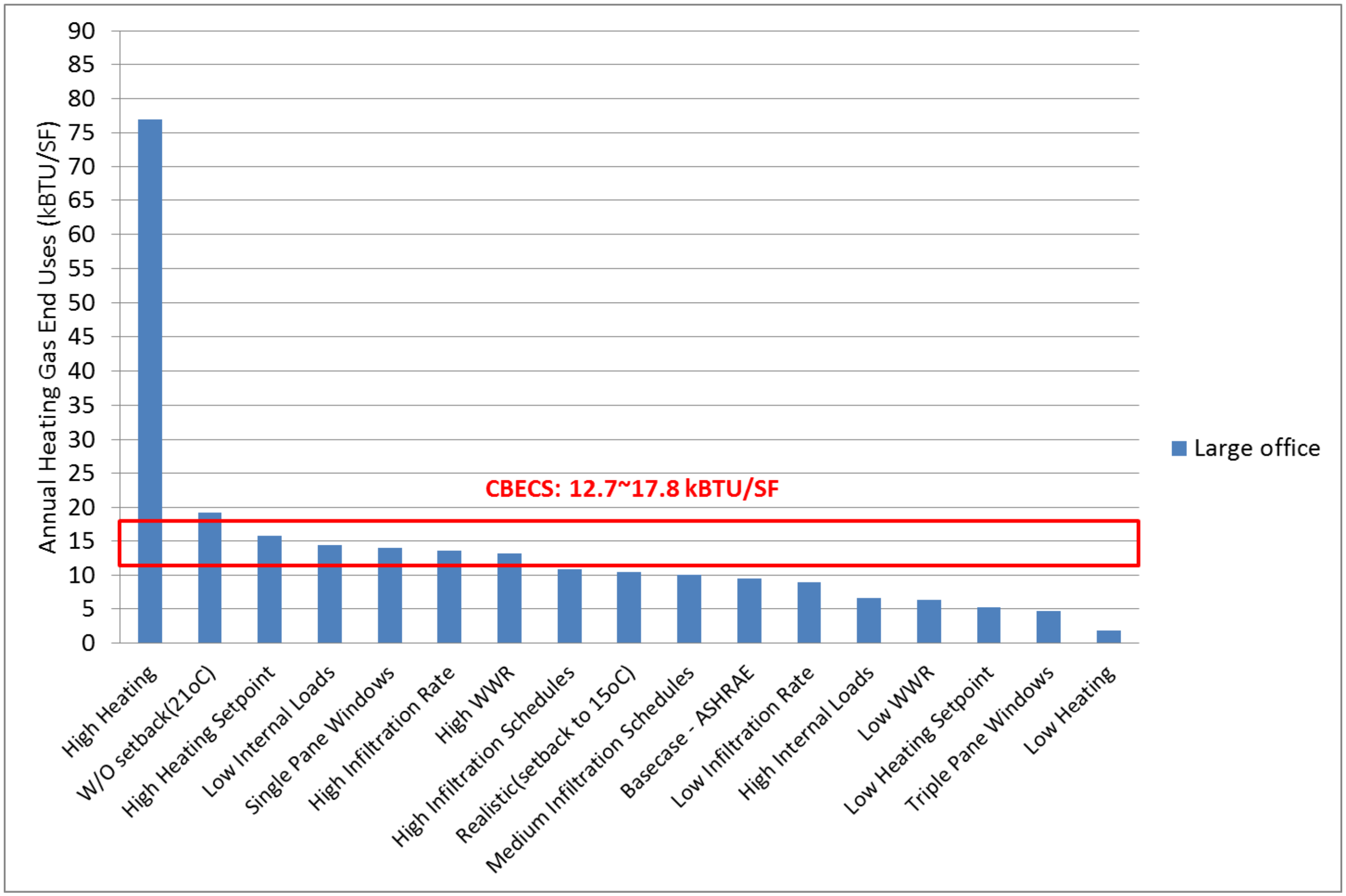
Whole Building EUI for the large office, Chicago and Fairbanks

Results (11)



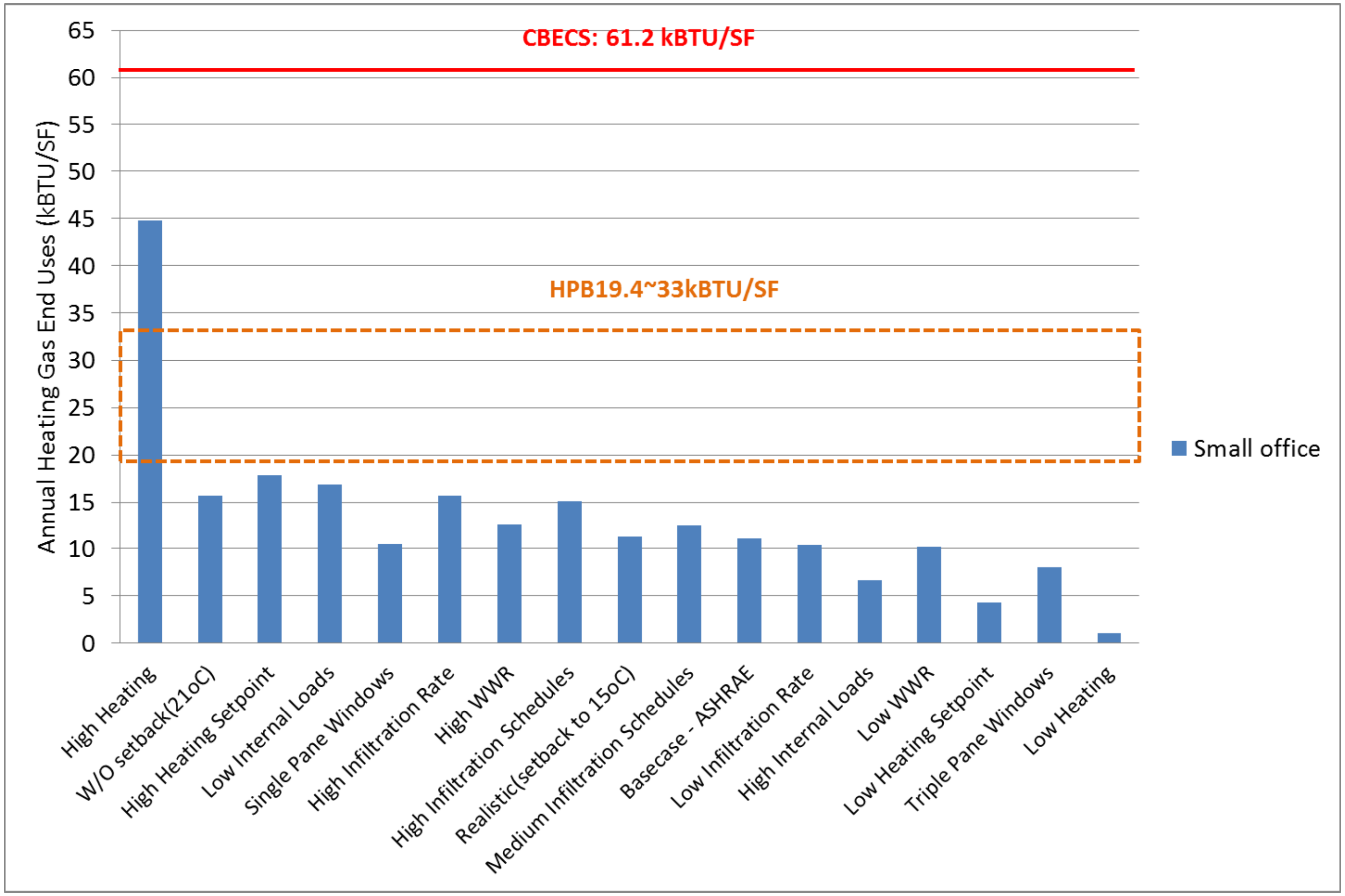
Space heating EUI for the large office in San Francisco

Results (12)



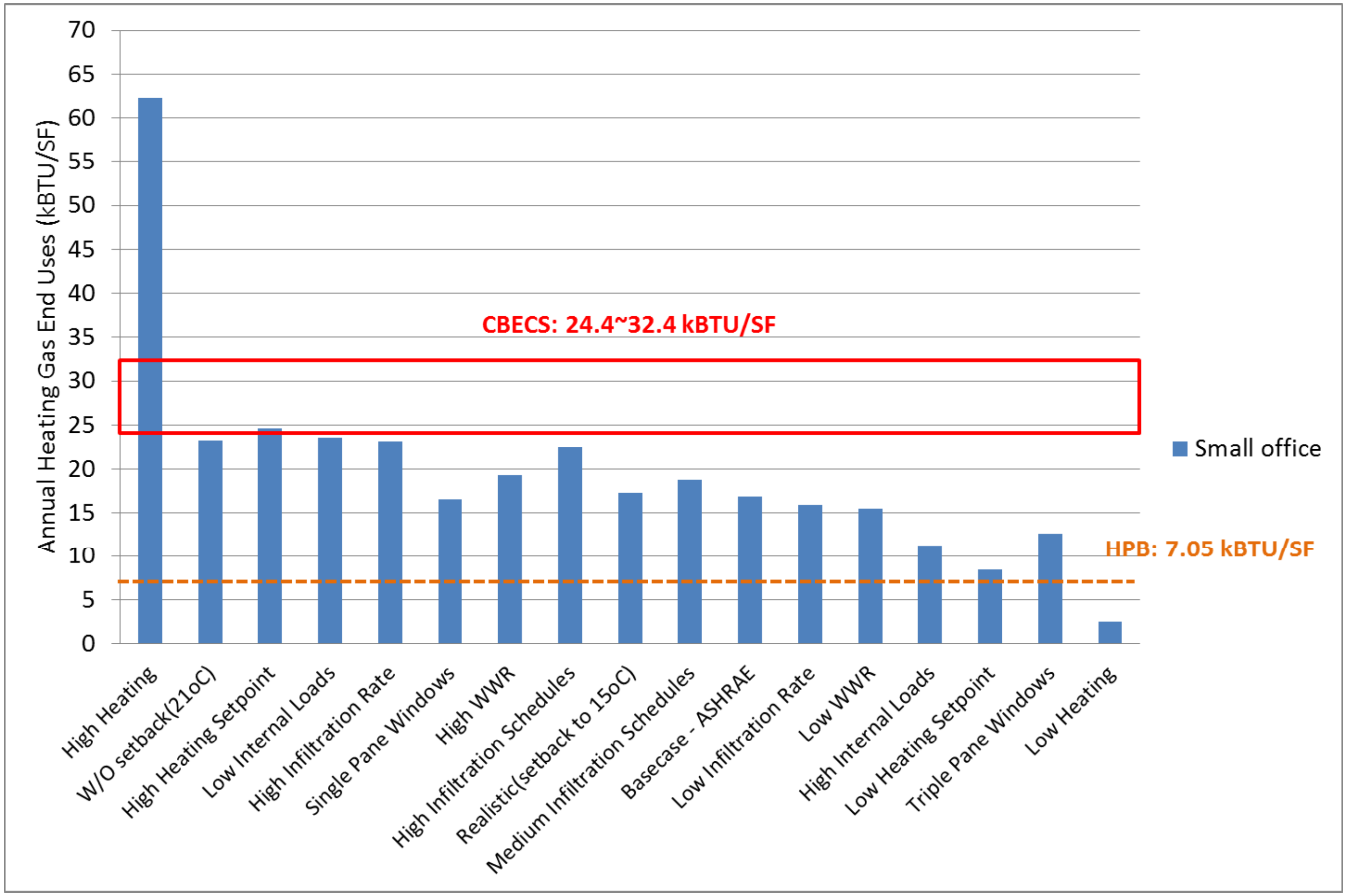
Space heating EUI for the large office in Chicago

Results (13)



Space heating EUI for the small office in Chicago

Results (14)



Space heating EUI for the small office in Minneapolis

Conclusions

- Space heating energy use can vary widely depending on a few key inputs
  - Minimum damper position of VAV box
  - Heating setback
  - Heating temperature setpoint
  - Infiltration rate and schedule
  - Window construction type and window area
  - Internal loads
  - Weather data
- The large and small office buildings from the DOE CRBs may under-estimate space heating energy use due to the use of:
  - Small infiltration rate
  - Ideal infiltration schedule
  - Ideal heating setback
  - TMY2 weather data

Better Simulation – Engine (1)

Evolving simulation engines that

- Can easily add or enhance modeling capability
- Can model equipment faults and operation problems
- Better handle human behavior
- Communicate with other engines

Enhancements to EnergyPlus

- Dynamic windows – thermochromic, electrochromic
- Shading controls
- Daylighting controls
- VAV controls
- Code compliance – CA Title 24, ASHRAE 90.1
- Demand controlled ventilation
- Adaptive comfort
- Model HVAC faults

Unconventional Systems

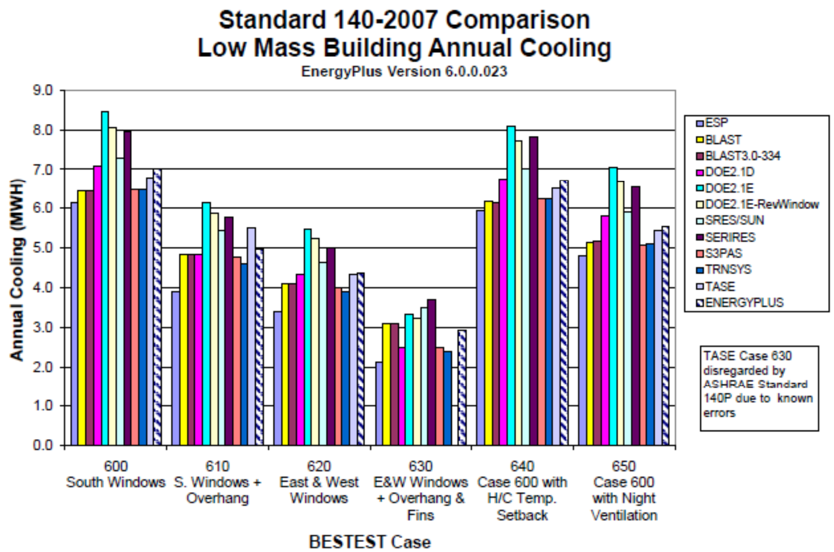
- **Smart facades**
- **Demand response**
- **Solar-powered heating and cooling systems**
- **Radiant cooling and heating systems**
- **Ground source heating and cooling systems**
- **Natural ventilation and mixed-mode**
- **Integrated controls strategies**

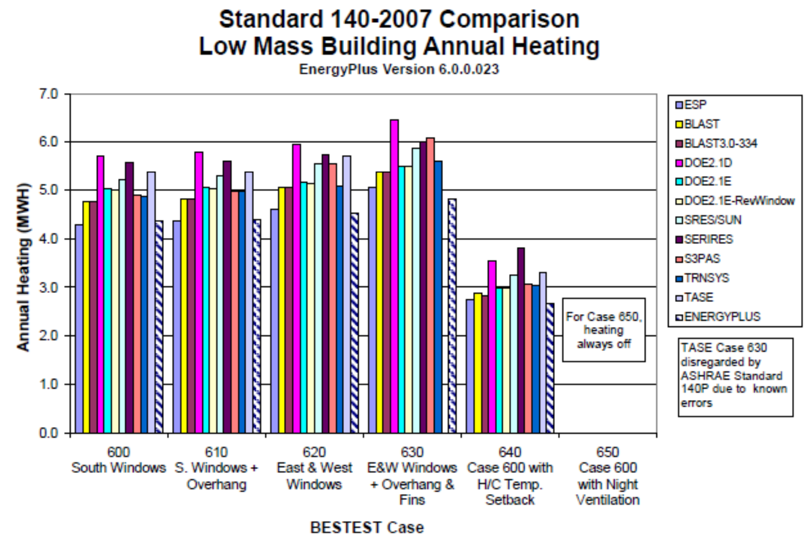
Better Simulation - Engine (2)

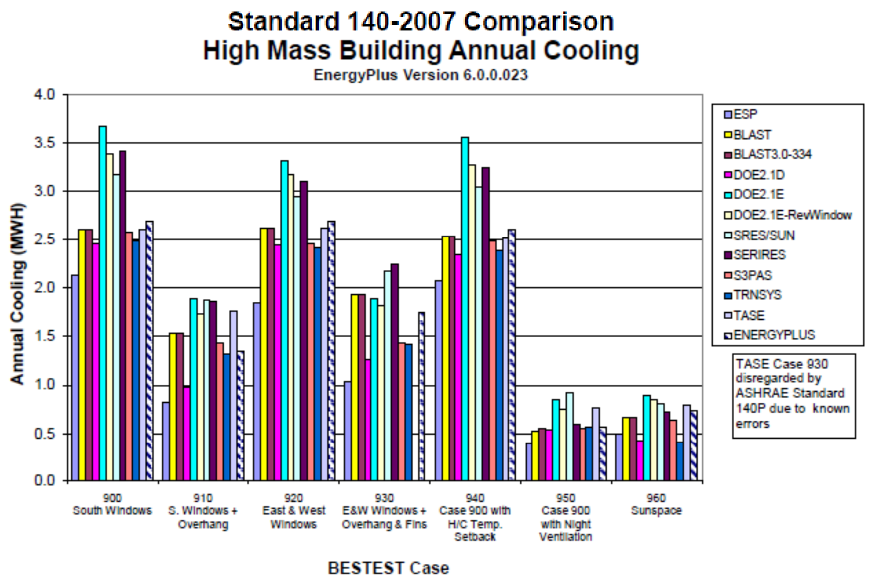
Testing and Validations – EnergyPlus

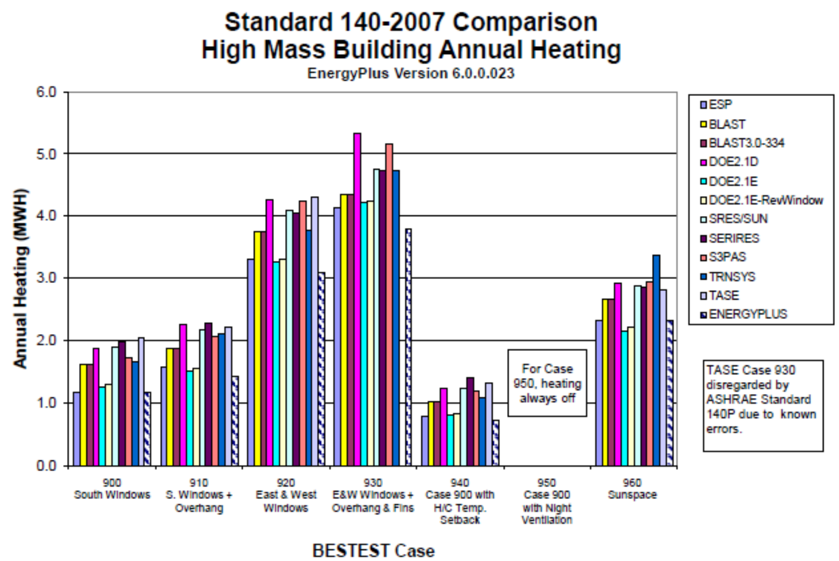
- Analytical tests:
  - HVAC tests, based on ASHRAE Research Project 865
  - Building fabric tests, based on ASHRAE Research Project 1052
- Comparative tests:
  - ANSI/ASHRAE Standard 140
  - IEA BESTEST
  - EnergyPlus HVAC Component Comparative tests
  - EnergyPlus Global Heat Balance tests
- Release and executable tests
- **<u>Empirical tests – very limited, not adequate!</u>**

ASHRAE Standard 140 Tests









Better Simulation - Platform

- Integrated Simulation Platform
  - A key part of the **Virtual Buildings Platform**
  - Various tools for different applications
  - Different design phases
  - Built on BIM (Building Information Modeling)
  - Parametric runs and optimization to support design decisions
  - Visualization, “seeing is believing”, better communicates
  - Real time simulation (LBNL BCVTB)
  - Continuous calibration of models
  - <u>**Built-in quality controls**</u>
    inputs, outputs, simulation process

Better Simulation - Standards

Develop standards of building performance simulation

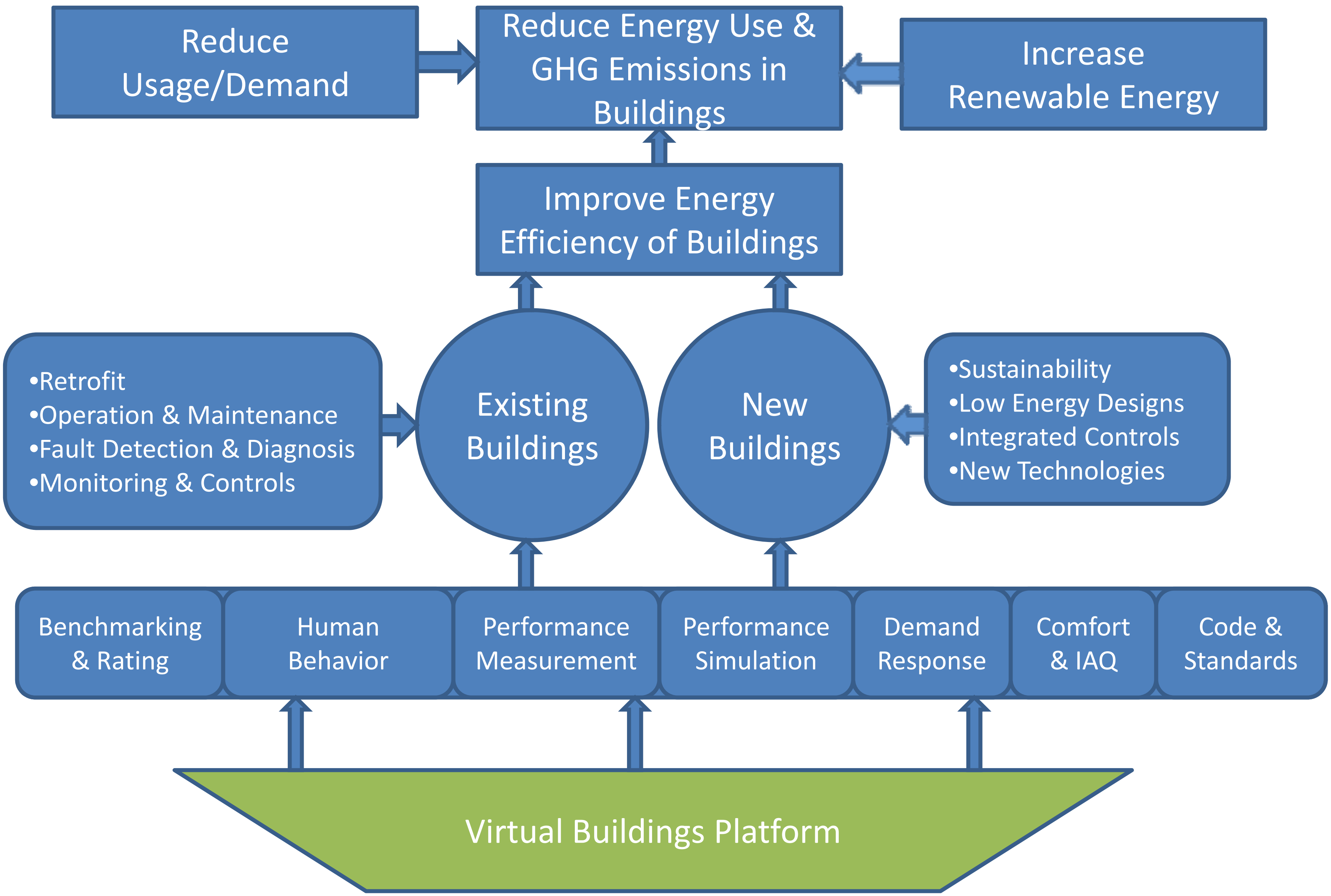
- modeling procedures + resources + reporting + testing (COMNET/RESNET)
- quality controls
- Equipment performance data (ASHRAE GPC 205)
- BIM

Better Simulation - Modelers

Professional Modelers

- Education
- Training
- Certification – ASHRAE BEMP
- Resources

Smart Tools, Dumb Modelers? No!
Professional Modelers with Good Tools! YES!



Research Portfolio of Energy Efficiency in Buildings

Sitert-Øksendal (1985)

“We have not succeeded in answering all our problems. The answers we have found only serve to raise a whole set of new questions. In some ways we feel we are as confused as ever, but we believe we are confused on a higher level and about more important things..."